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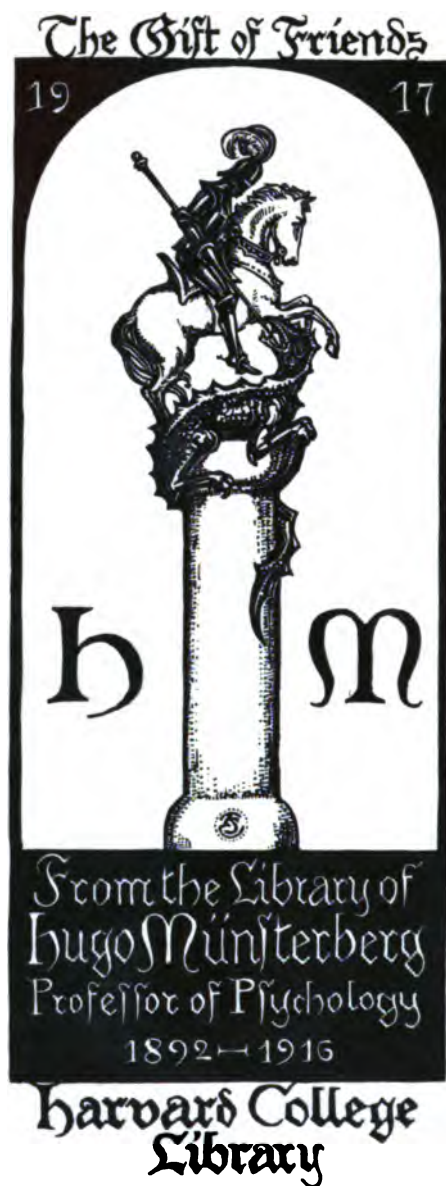
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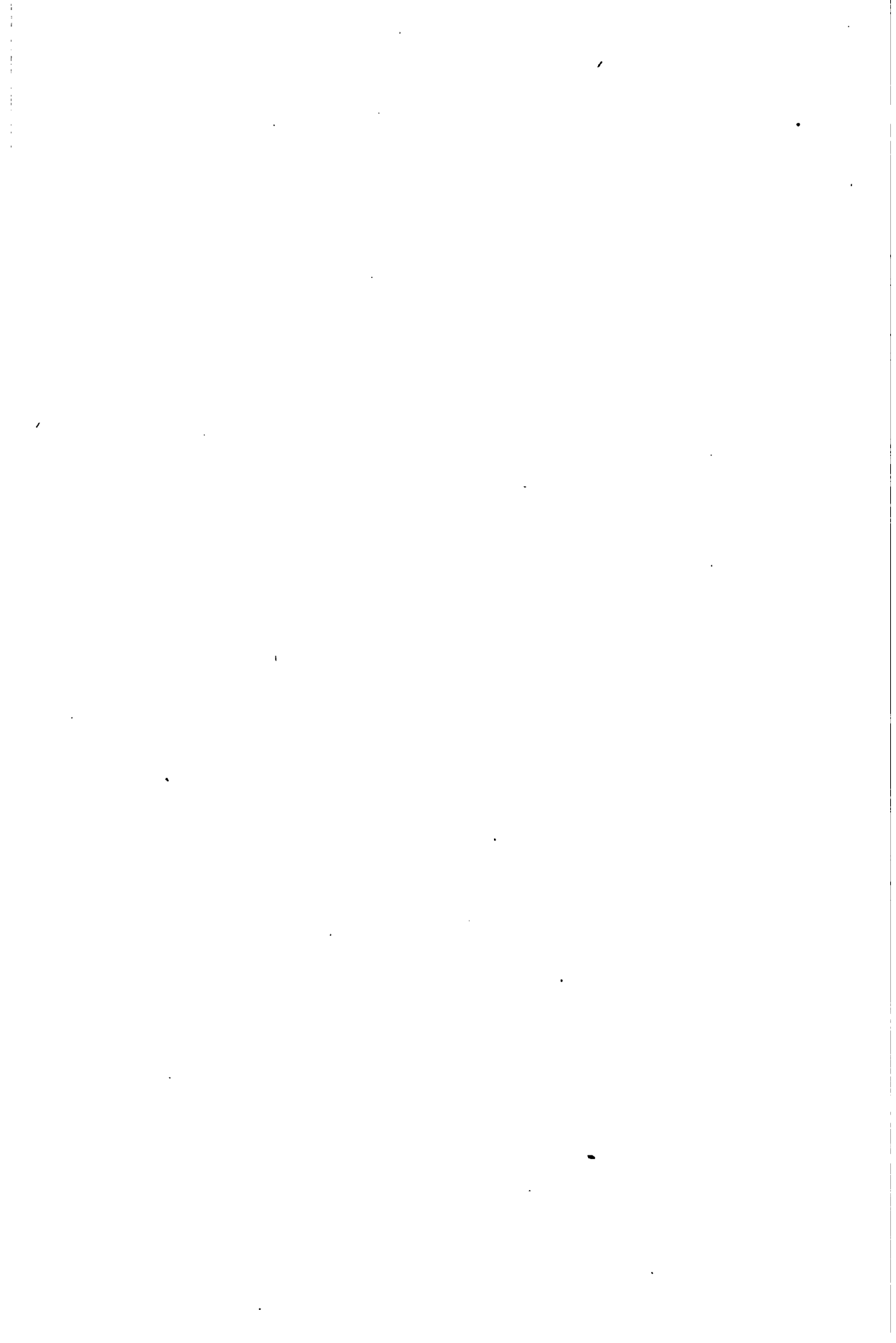


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DEPARTMENT OF COMMERCE

TECHNOLOGIC PAPERS
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BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 12

ACTION OF THE SALTS IN ALKALI WATER
AND SEA WATER ON CEMENTS

BY

P. H. BATES, Chemist

A. J. PHILLIPS, Assistant Chemist

and

RUDOLPH J. WIG, Associate Engineer Physicist

Bureau of Standards

[NOVEMBER 1, 1912]



WASHINGTON
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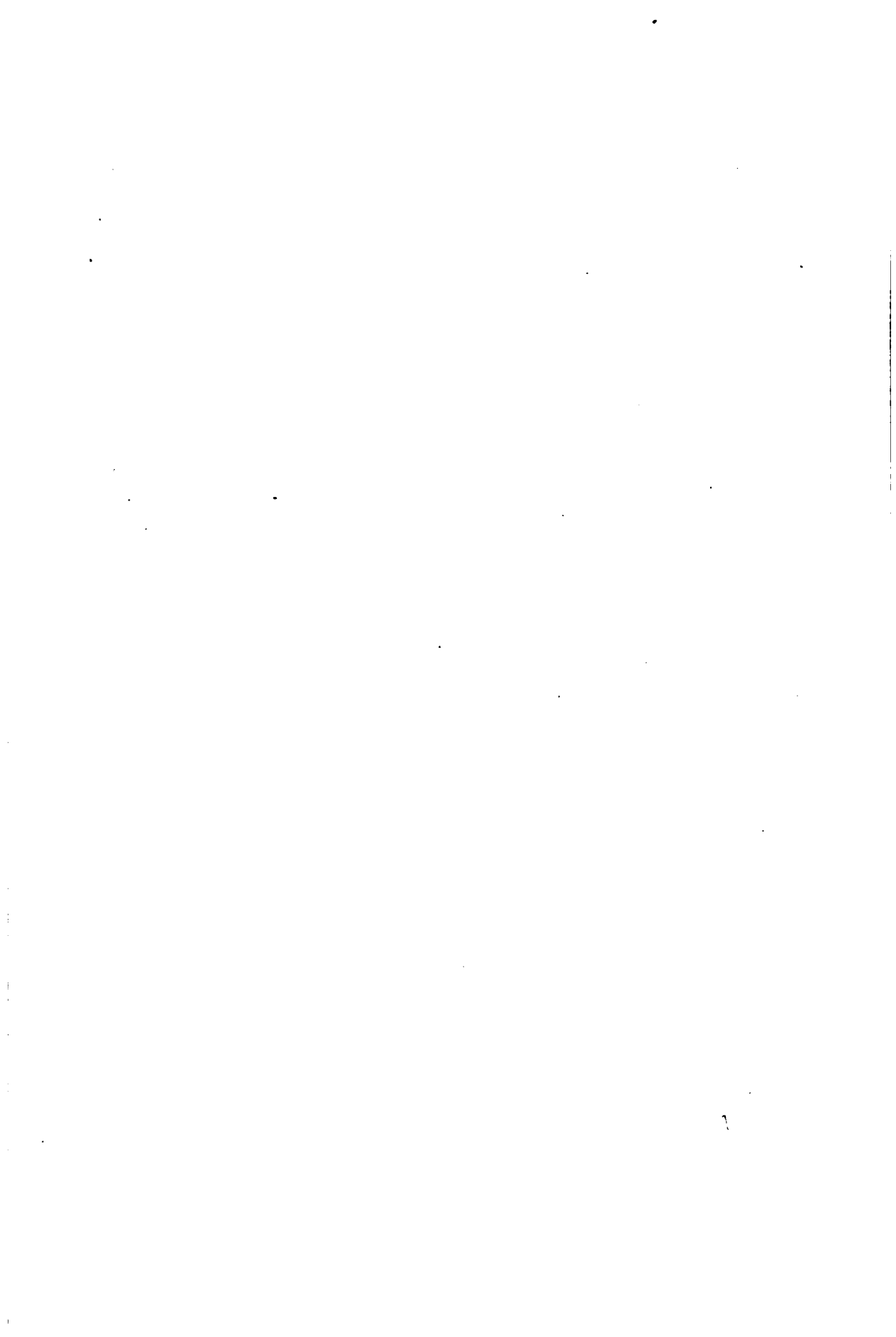
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(Continued on page 3 of cover.)





*Disintegrated concrete and boulders, showing alkali in crevices, at
Lateral "W," Shoshone Project, Wyo.*

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PREFACE

The investigations reported in this paper were started in the Structural Materials Testing Laboratories of the Technologic Branch of the United States Geological Survey, of which Mr. Richard L. Humphrey was Engineer in charge. This investigation, together with the force engaged upon it, were transferred to the Bureau of Standards July 1, 1910, the investigation being continued and completed by the authors.

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ACTION OF THE SALTS IN ALKALI WATER AND SEA WATER ON CEMENTS

By P. H. Bates, A. J. Phillips, and Rudolph J. Wig

PART I

I. INTRODUCTION

The disintegration of cement structures, when placed in contact with sea water, is a phenomenon, which has attracted the attention of cement manufacturers and cement users almost from the first time that such material was used for marine construction. There are cement structures which have withstood the action of sea water for years and probably will continue to do so yet there are structures which have failed; and it is also possible in the laboratory by artificial solutions to destroy almost completely a briquette, or cube, or cylinder made of cement mortars or concrete. The cause of this disintegration is not certain, though it is almost universally believed that it is the reaction of sulphate of magnesia of the sea water with the lime of the cement (formed during the setting) and the alumina of the aluminates of the cement, resulting in the formation of hydrated magnesia and calcium sulpho-aluminate, which crystallizes with a large number of molecules of water.¹

The other constituents both of the sea water and the cement are usually considered of little effect, though lately attention is being drawn to the fact that both sodium chloride and magnesium chloride rapidly attack the silicates.²

¹ Le Chatelier in *Tonindustrie Zeitung*, 88, p. 931; also "Experimental researches in the constitution of hydraulic cements." Candlot, *Ciments et Chaux Hydrauliques*, p. 306. Michaelis, *Bul. de la Soc. D'Encourag. de l'Ind.*, June, 1897.

² Candlot, *Ciments et Chaux Hydrauliques*. Michaelis, *Bul. de la Soc. D'Encourag. u.* 1890, p. 682. D'Rohan, *Engineering Record*, July 20, 1910. Michaelis, *Tonindustrie Zeitung*, Oct. 9, 1909. Schuljatschenko, *Through Cement*, 1901, p. 291. Rebuffat, *Gazz. Chim. Ital.*, 81, No. 55. Poulsen, *Ten Years' Report of the Scandinavian Portland Cement Manufacturers' Association*, through *Concrete Constructional Engineering*, vol. 5, No. 1.

Concrete structures have been made (especially in this country) which are resisting the attack of sea water to a marked degree. It is therefore not surprising that many engineers attribute the disintegration when it does occur to poor workmanship or materials, or to the abrasion of the sand or floating bodies in the water, and to the mechanical action of waves and frost action (as the disintegration usually takes place at or near the water line) rather than to any chemical reaction or crystallization due to such reaction.

It is not surprising that when cement structures were first placed in our arid regions this disintegration was not considered, though it was well known that these regions contain large quantities of magnesium sulphate, which, together with the sodium sulphate, forms the principal salts of the so-called "white alkali" in distinction from the black alkali, which is largely sodium carbonate. However, a short time after these structures were placed it was noticed that there was a softening of the mass along the water line and in due time this attracted considerable attention. It was investigated first by the Colorado State Agricultural College³ in the case of some disintegrated cement tile; and the Montana State Agricultural College in the case of the sewers and culverts of the city of Great Falls.⁴

These investigators, however, do not discuss the cause of the destruction other than to mention the sulpho-aluminate of lime formation, and in the case of the cement tile to mention that the silica and alumina were removed.

As the United States Government has been locating a large number of its irrigation projects in such regions, it was considered to be within the scope of the investigation of the Structural Materials Laboratories to make a study of this condition. Mr. Richard L. Humphrey, engineer in charge of the laboratories at this time, visited the Bellefourche project in South Dakota, the Shoshone project in Wyoming, the Sun River project in Montana, and the cities of Great Falls and Billings, Mont. In all of these he noticed alkali disintegration of the concrete, stones, and brick, and collected samples of the water, the alkali efflorescence and the soils,

³ Colo. State Agr. Col. Bull. 132, Destruction of Concrete by Alkali.

⁴ Mont. State Agr. Bull., The Effect of Alkali on Portland Cement.

also a few samples of disintegrated concrete. The alkali proved to be the characteristic white sulphate alkali, some analyses of which are given in Table I, p. 106.

As a rule it was noticed at the projects visited that with increasing amounts of magnesium sulphate disintegration was greater, although this was not always the case. As it had been previously found in sea water, this action occurs at the water line, extending from the low-water line to a few inches above the high-water line, caused no doubt by the concentration of salts at this point from the evaporation of the water. In the case of structures placed in damp earth—as the wings of “drops” or “gates”—it was found that the action extends from a few inches below the surface of the earth to several inches above it. Below the surface of the earth the concrete was soft and a trowel or knife could readily be pushed into it. There was also some swelling. Above the surface the mass was much drier and harder, but was swollen and readily pulled off in layers. Not only was the concrete noticeably disintegrated, but bricks, sandstone, and even granite (though to a small extent) were also disintegrated. A piece of spalled sandstone from the courthouse at Great Falls and another from the First National Bank Building at Billings showed the following sulphate and chloride present:

	Na_2SO_4	K_2SO_4	CaSO_4	MgSO_4	NaCl
Great Falls.....	16.16	4.69	2.62	23.60	0.47
Billings.....	31.02	2.97	5.62	30.84	5.58

This phase of the disintegrative power of alkali on these building materials, usually used in place of concrete, has not been generally noted; and when it occurs in such materials, relatively so inert chemically, it would seem to point to the fact that the crystallization of the salts already present in the alkali can cause great destruction, without assuming that there is any chemical reaction with the cement.

Later the Truckee-Carson project in Nevada, the Umatilla project in Oregon, the Klamath project, Oregon, and the Sunnyside and Tieton projects in Washington were visited. But very

little disintegration was noticed. There was plenty of alkali in the first project mentioned, but with the exception of the case of a small "drop" no action was visible. The same applies to the other projects, where no disintegration whatsoever was noticeable.

II. SCOPE OF INVESTIGATIONS

These investigations were planned for the purpose of determining the suitability and permanency of various cements in structures exposed to the chemical and mechanical action of sea water and alkali salts and, if possible, the cause of failure or disintegration of cements and concretes.

The study of the subject was begun in such a manner as to determine, if possible, just what reaction would take place when the salts, commonly present in sea water and alkaline soils, were allowed to act on cement and cement mortars. In order that this study should be complete, information should be obtained not only as to what salts present in any solution might cause destruction, but also in what manner this destruction is being accomplished. Both chemical and physical investigations were made in the laboratory, and field tests in sea water were made at Atlantic City, N. J. In both series of laboratory tests reported in Part I of this paper there have been used at various times, in addition to sea water from Atlantic City, solutions of sodium chloride, sodium sulphate, sodium carbonate, magnesium chloride, magnesium sulphate, ferrous sulphate, and also solutions in which there were present in equal parts by weight two salts as sodium chloride-sodium sulphate, sodium chloride-magnesium chloride, sodium chloride-magnesium sulphate, sodium sulphate-magnesium sulphate, sodium sulphate-magnesium chloride, sodium chloride-sodium carbonate, sodium chloride-calcium chloride, sodium sulphate-sodium carbonate, magnesium chloride-magnesium sulphate. It will be noted that a solution of calcium sulphate was not used. This salt is comparatively insoluble, and a series of tests using it, even in a saturated solution, would hardly be comparable with the series in which the above were used and in which the solutions contained but 2 per cent by weight of the anhydride salts. Moreover, when this solution contained the

sulphuric anhydride radical, calcium sulphate would be formed in the cement. The field tests made at Atlantic City are reported in Part II of this paper.

III. PHYSICAL LABORATORY INVESTIGATION

This investigation, comprising three series of tests, consisted of making of cement mortar, hollow cylinders closed at one end, 3.5 inches outside diameter, 10 inches high, with walls and base 0.5 inch thick, and permitting various solutions to percolate through.

FIRST SERIES

The cylinders for this series were made of mortar in the proportion of 1 part Portland cement to 2 parts sand and mixed to a dry consistency, thus giving a very porous and rich mixture with good cause for disintegration, namely, a large percentage of voids in which the salts could crystallize and a large amount of cement to afford possible chemical action.

The test pieces were aged for one month in water, when the open end was closed with a two-hole rubber stopper and connected with an aspirator bottle in such a manner by a constant level apparatus that they were maintained about one-third full of the solution. The solution percolated through and the appearance of the cylinder was noted from time to time. This was continued until the pores of the cylinders were so clogged with precipitated and crystallized salts that the solution would no longer percolate. The constant level apparatus was then discontinued and the aspirator bottle raised until a head of 5 feet was obtained. Until the end of the tests all the solutions containing magnesium, excepting the sea water, ran through these porous cylinders under this head. From this the relative disruptive force of the different salts could be noted.

From these tests it was seen that all the salts above enumerated would break the cylinders (excepting the sodium carbonate and the iron sulphate); yet the action was so much more severe with some than with others that it was decided in later experiments to use sodium sulphate, and magnesium sulphate, alone, equal parts of sodium chloride-magnesium sulphate, sodium chloride-sodium sul-

phate, and sea water. It will be noted that two of these solutions did not contain magnesium salts, yet the results obtained by these, as shown later, are very striking. The use of sodium carbonate was discontinued, because it was not perceptibly affecting the mortar (though it was leaching out considerable quantities of silica and alumina) and the action was shown only by analysis, the cylinders remaining intact and in good condition. The iron sulphate was discontinued for the reason that the lime in the cement was rapidly replaced by iron, which, being colloidal, clogged up the pores and prevented all percolation. Although the head was raised to 8 feet, it was not possible to force enough solution into the cylinders to cause destruction. It was not feasible to hold the stopper in under a greater head.

At the end of 45 days, while all cylinders were badly stained and in the case of the magnesium solution covered with the precipitated hydrate, there was no other visible sign of disintegration. They were therefore removed and a current of warm air forced in one of the two holes of the stopper, and at the same time the air around the cylinder was raised to about 100° F. When dry, the percolation was continued until 1 liter of solution had passed through. They were then dried again. At the end of the second drying the cylinders which had been treated with the mixed solution of sodium sulphate-magnesium sulphate and sodium chloride-magnesium sulphate were so badly cracked that the solution ran through the cracks without appreciably wetting the rest of the cylinder. The same thing occurred in the case of the single salt solution of sodium sulphate and magnesium sulphate after the third drying; with the mixed solution of magnesium chloride-magnesium sulphate and magnesium chloride-sodium sulphate after the fourth drying; and with mixed salt of sodium chloride-sodium sulphate after the sixth drying. Following the seventh drying the percolation was discontinued. By this time the sea-water cylinder was so badly clogged that the water would not percolate through. While disconnecting it from the apparatus it was overthrown and broke horizontally in two parts. All the other cylinders, except the ones treated with sodium carbonate and ferrous sulphate, as noted above, were cracked. In Fig. 1



Fig. 1.—Hollow cylinders composed of one part Portland cement to two parts sand after exposure to various solutions

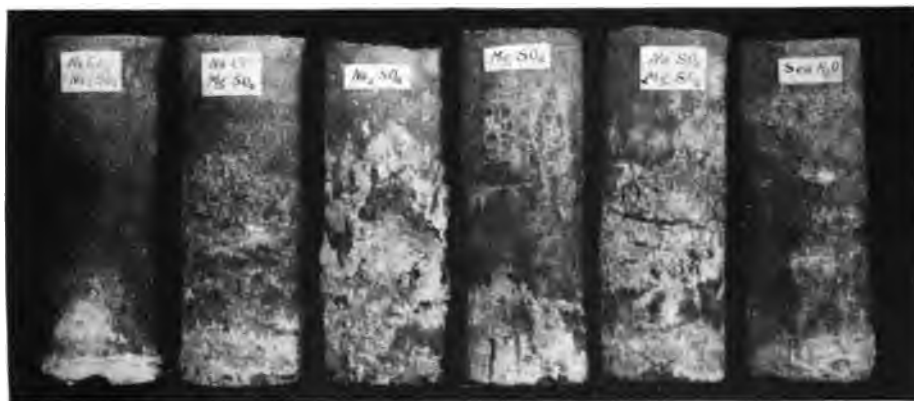


Fig. 2.—Hollow cylinders composed of one part Portland cement to three parts of sand after exposure to various solutions

these cracks appear as fine white lines—cracks filled with precipitated and crystallized salts. These are not shown very distinctly on the cylinder marked MgCl , owing to the fact that the remainder of the cylinder is covered with hydrated magnesia.

It is also noticed in Fig. 1 that the replacing of half of the sodium or magnesium sulphate present with sodium chloride does not decrease the apparent degree of destruction. It might be assumed that the amount of sodium or magnesium sulphate still left in the solution was sufficient for this purpose, but an inspection of the photograph shows that the destruction of sodium chloride-magnesium sulphate cylinders is greater than the magnesium sulphate alone. While it seems to be the reverse with the sodium salts, yet the crack with the sodium sulphate-sodium chloride cylinders was wide enough to allow the solution to run through without causing the rest of the cylinder to become sufficiently wet to do much damage. The disintegration of the sodium sulphate-magnesium sulphate cylinders is characteristic of alkali disintegration in general—i. e., a blistering on the surface and on removing this blister a soft crumbling mass of concrete underneath.

SECOND SERIES

In order to find, if possible, how much salt was necessary to cause disintegration, another series of six cylinders similar to the first series was made, but in the proportion of 1 part Portland cement to 3 parts of sand, which was mixed to a dry consistency.

These cylinders were placed in dishes in a room maintained at 100°F during the day, and at night the temperature was allowed to drop to about 60° to 70° . Immediately after making, the forms were removed and the solutions were poured around the top of the cylinders and allowed to flow down to the bottom, without any previous aging in water or air, but never pouring on more than enough to wet them. After 500 cc (containing 10 grams crystallized salt) of the solutions had been added the cylinder was thoroughly dried and examined for cracks, etc. In this manner it was hoped to determine how much salt was necessary for disintegration. After 50 grams of magnesium sulphate had been added to a cylinder two vertical cracks appeared, extending up

outside, another was painted similarly on the inside, the purpose of which was to see if it is possible to render them impervious in this manner. To another pair, also, sufficient barium chloride was added, dissolved in the mixing water, to give an amount of this salt present, equal to about twice the amount necessary to precipitate all the plaster (CaSO_4) present in the cement. Another pair was treated similarly with barium carbonate, this being in an emulsion with the mixing water. The purpose of this addition of barium salts was to see if it was possible to protect the mortar by having the sulphuric anhydride radical combine with the barium to form the insoluble barium sulphate with consequent clogging and protecting of the cylinder.

The cylinders thus made, as soon as they had acquired sufficient strength to allow of handling, were connected with a constant level apparatus as in the first series, using here the solutions used in the second series. But these cylinders were placed in a long box, through which hot air (100°F) could be forced. The cylinders stood in glass funnels, at the bottom of which valves were so arranged as to allow any solution which would percolate through the cylinders to drop out without allowing any air to be drawn in, as it was necessary on occasions to draw the warm air through instead of forcing it. In all other places the box was sealed, excepting one inlet and outlet. However, after using the constant level for two weeks it was found that there was no percolation, owing to the density of the mortar. Consequently, this was discontinued and the containers holding the solution were raised until a 5-foot head was reached. This head was maintained for four months. At the end of this time it was found that all cylinders (excepting those containing the barium salts) had been rendered impervious and were not allowing any solution to percolate through. The two cylinders which had been treated—the one on the inside and the other on the outside—with cement grout had never allowed any solution to run through. Those treated with the barium salts after several months gradually became porous and allowed the solution to come through in a number of minute pores. This result is rather difficult to explain; it was expected that there would be a precipitation of the insoluble

barium sulphate in contact with the sulphates of the solution, which it was hoped might clog up any voids, though it was hardly expected that this means could be used in construction work, owing to the cost especially of chloride. But apparently the barium sulphate occupied a smaller volume than the other barium salts, so that it was washed completely through the cylinders, and instead of "silting" it up rather increased the number of voids.

Noting that the cylinders, after four months, were remaining in good condition, the funnels were sealed at the bottom and then filled with the solution which had been used with the cylinders; at the same time the head was increased to 12 feet. The amount of solution percolating through the cylinders was very small, and it was evaporated by warm air as fast as it came through. As this treatment was causing almost no action, the cylinders were removed from the box and placed in a room kept at about 75°C in pans filled with sufficient solution to reach about one-third up the cylinder. At the same time the latter were kept filled with the solution. With three exceptions, after 15 months of this treatment there was practically no action. The cylinders were quite white on the exterior, but the salts did not seem to have penetrated or remained on the interior. Of the three exceptions mentioned above, two were those which had been placed in sodium sulphate solutions. At the end of three months they had been corroded or disintegrated to a depth of one-eighth to one-half inch at about 2 inches above the water line. This action had progressed slowly, the first appearance being a blistering. The blister increased considerably in size and finally flaked off. Another blister then formed underneath this and the action was continued. The third of the exceptions mentioned was a cylinder treated with sea water, which was removed at the end of five months, the action being similar to that of sodium sulphate. All the other cylinders at the end of the 15-month period were in very good condition. The one immersed in the solution of sodium chloride-magnesium sulphate showed a very slight blistering. The one immersed in sodium sulphate-magnesium sulphate had a vertical crack extending about one-third of the distance down from the

top of the cylinder. The cylinders grouted, both on the exterior and interior, were in first-class condition and, contrary to the usual opinion, the grouting had not separated from the remainder of the mass, but was as firmly bonded as ever. There was no corrosion of the specimens containing the barium salts, but they were badly stained with magnesium hydrate, showing that they had allowed the solution to percolate through them. This staining was almost entirely absent on all the other cylinders. It might be remarked that this blistering or corroding of the cylinders is very characteristic of the alkali action in the western arid regions. The cracking, as obtained in the other series, is not common in that district.

It is obvious from the above results of these physical tests that a pervious mortar (and almost of necessity a pervious concrete) can be destroyed by almost any salt if a sufficient amount of it is allowed to accumulate in the mortar and then a rapid formation of crystals is brought about by drying; and as larger crystals are formed by slow crystallization there would be obtained the same results on a larger scale, but in a greater time, if a slow-drying was used. Sodium carbonate is not excepted in this statement, as it must be remembered that these salts were allowed to percolate through the cylinders, and consequently products of chemical action were removed. This is also true in the case of the magnesium salts, where voluminous precipitates of the hydrate were obtained in the bottles placed under the cylinders to catch the dripping, though at the same time a heavy precipitate was obtained in the cylinder. This third series shows the value of a dense mortar. These tests were carried to a greater length and under severer conditions than the others, yet the results obtained were much better than in the previous ones. It also seems to be evident that a drying or an evaporation is necessary for disintegration to take place. This was particularly noticeable in the first series, where the cylinders remained intact until dried and where even the first drying in several instances produced large cracks and the second drying in two cases caused complete destruction. This action was very strikingly shown by applying Brard's tests to stone. This is a freezing test where the freezing (crystallizing) of a salt is used to produce disruption of the stone.

Having in mind the disintegration of concrete under the influence of salt, there was included in the test three briquettes and three 2-inch compression cubes of an unknown proportion (they happened to be some test pieces lying in the laboratory—doubtlessly were 1:3). The test was usually carried out by immersing the specimens in a saturated solution of sodium sulphate and boiling for 1 hour, removing, allowing to dry 24 hours, washing off the crystallized salt, reimmersing in the solution, reboiling, etc., 10 times, then noting any loss in weight, the general appearance, and also obtaining the compressive strength. The cement specimens after having been treated 10 times in this manner were apparently unchanged, and were consequently returned and boiled 6 times more without replacing the water evaporated. At the end of this time they were still unchanged and were replaced in the solution and allowed to remain for a month, two briquettes and one cube projecting above the solution about one-quarter of an inch. They were then examined, and it was found that the surfaces out of the solution were badly cracked; that there was only about one-half an inch of solution and the remainder was a solid mass of sodium sulphate. By heating this was dissolved, and it was found that the remainder of the partly immersed specimen was in good condition, the cracks uniting in a very remarkable manner just below the water line. It was also found that the totally immersed specimens were apparently unchanged. All were then left out of the solution, and at the end of another month, on trying to handle one, it crumbled to a mass of powder. All of the others also fell to pieces on handling, though they had retained their original form and appearance, except a whitening due to the effloresced sodium sulphate.

It is possible that the production of efflorescence can play a prominent part in the destruction of a porous medium in which a crystallized efflorescible salt has separated. While there are no data on hand on the force which would be exerted by a crystal losing its water of crystallization and changing to a powder, yet there is some evidence that it is considerable. It must be mentioned, however, that this is not due to a true change in volume, but only to an apparent change, the effloresced material appar-

ently occupying a much larger volume than the crystallized, although it really occupies a smaller volume.

IV. CHEMICAL INVESTIGATION

The purely chemical investigation consisted in taking 10 grams of a Portland cement to which no plaster had been added by the manufacturer (for analysis, see Table 2), placing it in a flask, and adding 500 cc of 1 per cent solution of various salts and shaking, not allowing the cement to set. At various periods the solutions were withdrawn and analyzed and fresh solutions of the same concentration and composition added. By this means it is possible to determine what the cement has lost to the solution and what the solution has lost to the cement. The same cement, after setting and grinding, as described below, was similarly treated, these two cements being used throughout the investigation. A larger number of solutions was used in the tests of the unset cement than in the physical tests, using in addition to those enumerated, calcium chloride, calcium chloride-sodium chloride, and calcium chloride-magnesium chloride. With the set cement a smaller number was used, this being done in order to curtail the amount of analytical work necessary, and because it was found with the unset cement that certain solutions were very inactive. The set cement was prepared by mixing the same cement as used in the unset series with 25 per cent of water and placing in briquette molds. This was allowed to set for two weeks, the molds with the briquettes being placed between two pieces of plate glass, thus protecting the cement from the action of the carbon dioxide of the air. It was then removed from the molds, ground, passed through a 200-mesh sieve, mixed with 20 per cent water, replaced in the molds as before, and allowed to set two weeks longer, and ground as before.

The shaking of a small quantity of cement with a large quantity of solution is open to some criticism on the ground that it is not a condition ever occurring in actual practice when there is only a surface of set cement reacting with the solution, and therefore the greater part of the insoluble products if this reaction are deposited on the surface, and tend largely to hinder further action. At the same time the soluble products are immediately removed,

which tends to reduce the possible amount of crystallization of these salts. However, on the other hand, the abrasion of fine sand in water, or the abrasion of the waves themselves, would have a tendency to prevent the deposition of any reaction products; while in the case where a solution comes into contact by capillarity alone, as it most frequently does above the water line where disintegration is greatest, these objections do not hold good or are largely modified. It was therefore thought that the ultimate results of the action of any salt could be best and most quickly studied by bringing the cement particles into close contact with the solution. As will be seen later, even with the particles of a degree of fineness that would insure the cement passing the specifications and with frequent shaking of the solutions and cement, the particles were coated with reaction products which reduced considerably the rate of action but did not prevent it finally. Consequently, such a series with a certain salt would show what the final results on a particle of cement would be in actual practical conditions, though the rate of the action may under certain conditions be reduced and in others accelerated.

In making this study it was thought necessary to use both set and unset cement, as it has been positively predicted that even if the action was rapid with the unset cement, it would necessarily be much slower or entirely absent with the set, since by the setting the constituents have reached a more stable condition; whereas with the unset material in the solution the lime would be seized as set free and react with the salts present and never have an opportunity to exert its usual function in the setting. However, it might be remarked that in the majority of large structures, where salts may act on concrete, only a very short time elapses between placing the concrete and its coming into contact with these salts.

Our experiments, however, did not bear out this prediction, as the set cement was decomposed more rapidly. Had the cement been set in the air or running faucet water the results might have been as predicted, for in such a case during the setting, grinding, and resetting particles which in the present case were coated with hydrated lime would have been coated with the inert carbonate of lime. The experience of this laboratory has been that during

the setting of cement, mixed with and stored in faucet water, dried, ground, and the treatment repeated, without any care being taken to prevent CO_2 absorption, from 6 to 14 per cent CO_2 will be absorbed.

In the present case only distilled water was used, and particular pains were taken to exclude the CO_2 . Only 1.98 per cent of CO_2 was absorbed.

There was another rather striking difference between this set and unset cement, both having come from the same bag. The experiments of Michaelis^a and Cabolet^b in particular have shown the rapid swelling of different cements when placed in an excess of water and shaken, not allowing the cement to set. This increase in volume, occupied by the cement, will in certain cases be as great as seven hundredfold. This reaction is the formation of colloidal gels from the crystalline particles of cement under the influence of the soluble lime and to a less extent from gypsum, as electrolytes. Cabolet claims that the swelling starts when from 0.25 to 0.29 gram per liter of lime are present in the solution and that the maximum swelling is reached when the lime content of the water has reached from 45 to 65 grams per liter. It would seem, therefore, that the more readily a cement would yield up its lime the more readily would the swelling occur. Also the lime as it is liberated, being the constituent of the cement which reacts more readily with the solution under investigation, it would seem that the rate of swelling of a cement, shaken as above with a large excess of water, would be an index of the rate of its decomposition by sea water or other salts in solution. We have not any data to prove or disprove this statement, except in the case of the cement used in this investigation. After having set, as described above, it reached a maximum increase in volume of 150 per cent in 72 hours; whereas the unset cement increased but 30 per cent in 13 weeks, 50 per cent of this increase having taken place in the last week. A comparison of the data given later will show how much more readily decomposition was effected with the set material. The composition of the cement before and after setting is shown in Table 2, p. 108.

^a Thirteenth Annual Meeting of the Association of German Portland Cement Manufacturers; 1907.

^b *Ton. Zs.*, 33, p. 1019; 1908.

1. ACTION OF SOLUTIONS ON FRESH CEMENTS**(a) CHANGES IN THE LIME CONTENT**

In Figs. 3 to 7 are shown the results of the tests giving the percentage of lime lost by the cement in the presence of the various salt solutions. These solutions were carefully standardized from time to time and so much solution added that there would be 1 per cent of anhydrous salts acting on the cement, when the total weight of the solution had been brought up to 500 grams by the addition of water. Where two salts are present in the solution, 0.5 per cent of each was used. In the experiments where sodium carbonate was used the "lime lost" has been calculated from the amount of CO_2 removed from the carbonate solution. This has been done necessarily, since there was no lime removed by the solution, it having been converted into carbonate and retained in the residue as such. In the same manner it would have been desirable to calculate the amount of lime which had been converted into the insoluble sulphate in the presence of the sulphate solutions, but this was not done owing to the lack of information in regard to what sulphate of lime was formed; and also owing to the fact, as seen later, that the sulphate actually formed was returned into the solution later. A more complete discussion of this will be given when the action of the sulphate is considered.

It was early noticed that there was a great difference in the rate of decomposition as effected by the various solutions, especially so in the case of the sodium chloride-magnesium chloride solution, which at the end of the sixth week had removed 50.7 per cent of the lime. Unfortunately the flask containing this solution and the cement upon which it was acting was broken at this period, and a fresh test was not undertaken; but the results obtained here were made use of later. At the end of the thirty-eighth week it was noticed that all solutions, except the sodium carbonate, were acting comparatively slow, so that unless the tests were to be continued for an indefinite period it was thought advisable either to change one of the salts in the solution or discontinue the treatment. However, the treatment with the calcium chloride solution was the only one discontinued. In the other cases one of the salts was changed, obtaining very striking results.

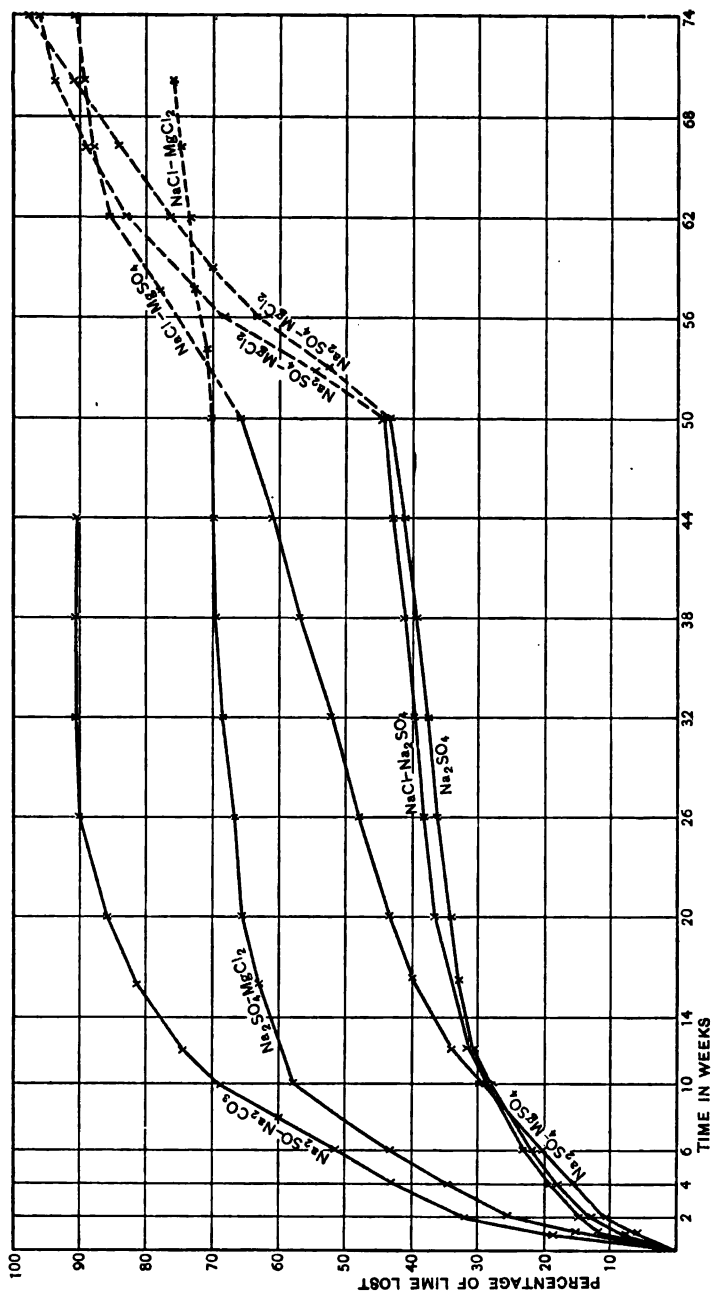


Fig. 4.—Percentage of lime lost by the unset cement to the sodium sulphate series of solutions.

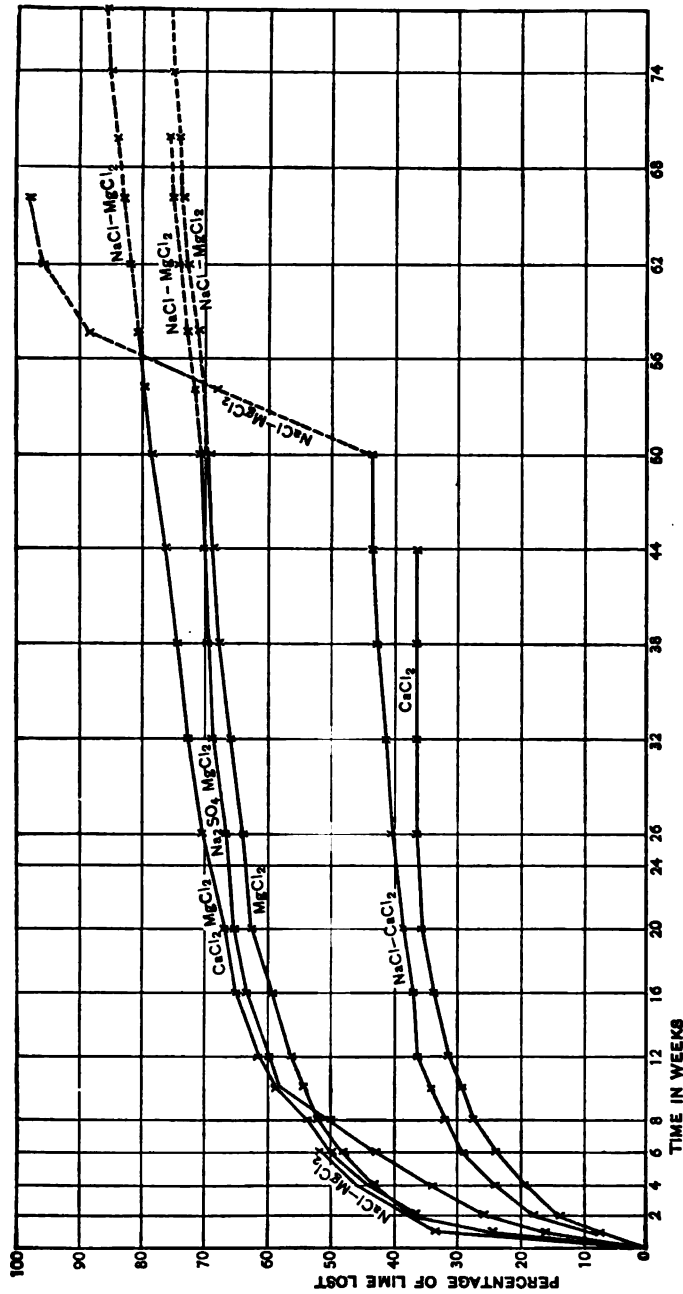


Fig. 5.—Percentage of lime lost by the unset cement to the calcium chloride and magnesium chloride series of solutions

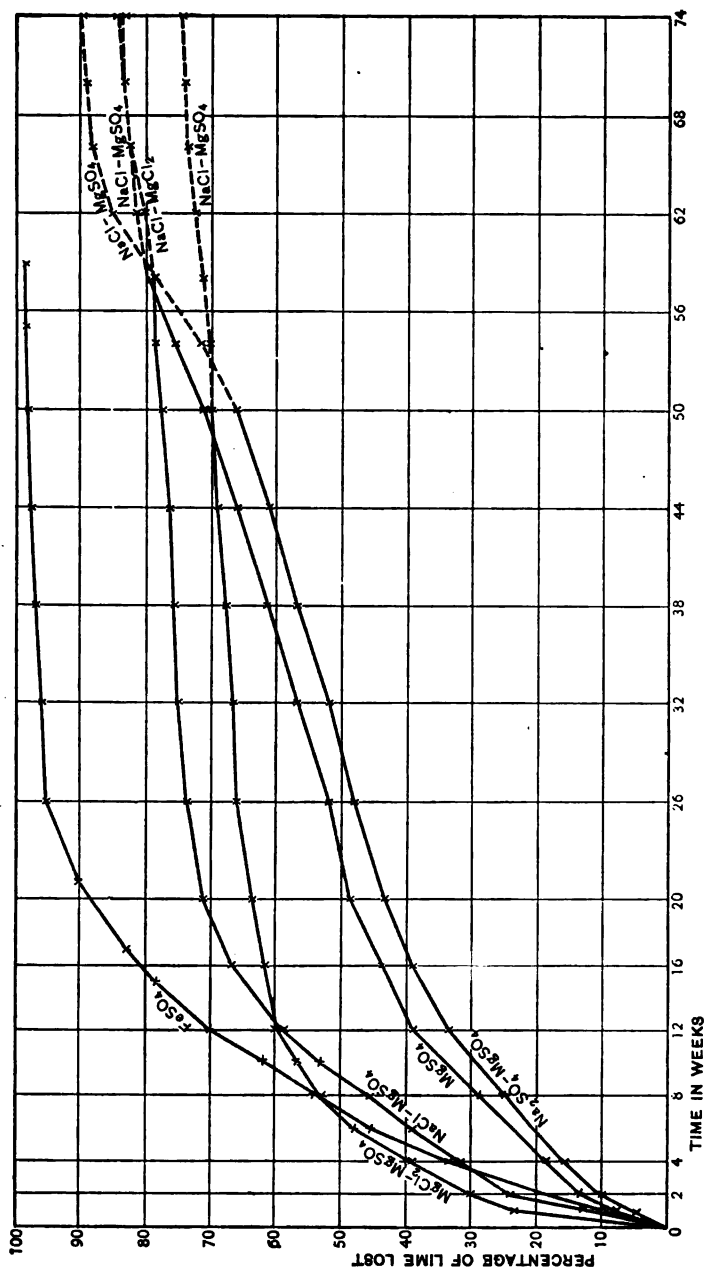


Fig. 6.—Percentage of lime lost by the unset cement to the magnesium sulphate and ferrous sulphate series of solutions

Up to this period, however, it may be said in general that the presence of sodium chloride in the solution has increased the decomposition of the cement. This holds true in each case except that of the solution sodium chloride-sodium carbonate. This action is all the more striking when it is remembered that the presence of the sodium chloride has reduced the quantity of the other salts by one-half. The presence of magnesium chloride has

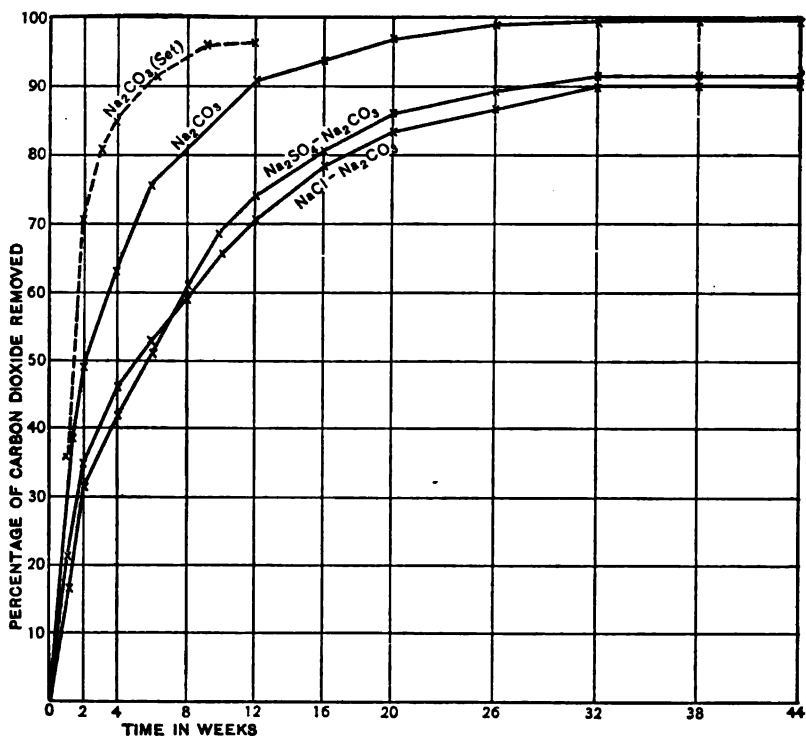


Fig. 7.—Percentage of carbon dioxide removed from the solution of sodium carbonate in terms of calcium carbonate, using set and unset cement

acted in the same way, but to a still more striking degree as is noticed in the solution sodium chloride-magnesium chloride. At the end of the thirty-eighth week the solution sodium chloride was changed to a solution containing sodium chloride-magnesium chloride, with the results that at the end of the forty-fourth week half as much lime was removed as there had been removed in the

entire previous periods. During the next four weeks an equally large amount was removed. The solution sodium chloride-sodium sulphate was changed at the end of the fiftieth week to sodium sulphate-magnesium chloride, and again there resulted a very large increase in the rate of decomposition of the cement. The various other solutions were also changed, and, with a few exceptions, the rates were decidedly increased. The changes made were such that the resulting solutions usually contained sodium chloride or magnesium chloride, the idea being to introduce one or both of these salts into the solutions, since they had been particularly active. By these changes two of the solutions contained sodium sulphate-magnesium chloride, and, as noted above, this combination was also very active.

The general conclusion drawn from these results is that the chloride solutions are more active than the sulphate solutions. Attention should be drawn to the fact that in the presence of the soluble sulphates some of the lime is fixed, temporarily at least, as a sulphate, and therefore does not appear in the solutions withdrawn; whereas, with the chlorides, all of the lime of the cement reacting with the solution immediately goes into the solution. This last statement apparently requires a slight modification, as later results seem to point to the removal of a slight percentage of chlorine from the solution. In actual practical conditions, where the disintegration of a concrete would of a necessity be almost entirely a surface condition, this condition would again result in the chloride being the more active, as the decomposition products are soluble and would immediately be removed, exposing a new surface. The sulphate decomposition products are not as soluble and would tend to protect the surface from further action. It is also noticed from the results that when a chloride is present with a sulphate in the solutions the resulting lime sulphate is much more soluble. Therefore it would appear that the protective action of the sulphate in such a combination would be decidedly decreased. Such a combination exists in sea water.

(b) CHANGES IN THE MAGNESIA CONTENT

The amount of magnesia removed from the various solutions is shown in Fig. 8. It will be noticed that after the first few periods during which in several cases the magnesia was entirely removed the quantity removed rapidly decreased. Beyond the fact that the amount removed from the solution is dependent entirely upon the amount of lime that goes into the solution, there is not much to be said, as the lime removals have been discussed sufficiently in the lime chapter. There was, however, in several cases a slight tendency for the magnesia to return into solution toward the latter part of the tests, noticeably in the magnesium sulphate solution when part of the magnesium sulphate had been replaced by sodium chloride.

(c) CHANGES IN CONTENT OF CHLORINE, IRON OXIDE, ALUMINUM OXIDE, SILICA, AND SODIUM OXIDE

During the early part of the experiments the chlorine and sodium oxide in the solutions were both determined, but it was soon found that the error in the determination of these two was so great unless carried out by the most careful methods, that it was discontinued. By the most painstaking care it was found that there was but a slight or no change in their content before and after agitation with the cement. For this reason also the determinations were discontinued, as the time available did not allow for such careful work when there was apparently no use for it.

The silica, iron, and aluminum oxides were determined regularly, but in no case did the percentage removed amount to more than 0.0005 per cent and usually about one-half that. Of course when sodium carbonate was present this does not apply, as the silica was removed in considerable quantities. (See Table 3 and Fig. 9.) Alumina was removed in very much less quantities. This is somewhat contrary to the usual opinion, though Candlot⁷ has called attention to it.

It was, therefore, thought advisable to make an analysis of the residue and to compare this residue with a residue calculated from the amounts of lime, magnesia, and sulphuric anhydride removed or precipitated during the various periods. In making these cal-

⁷ Candlot, *Ciment et Chaux Hydrauliques*, p. 312.

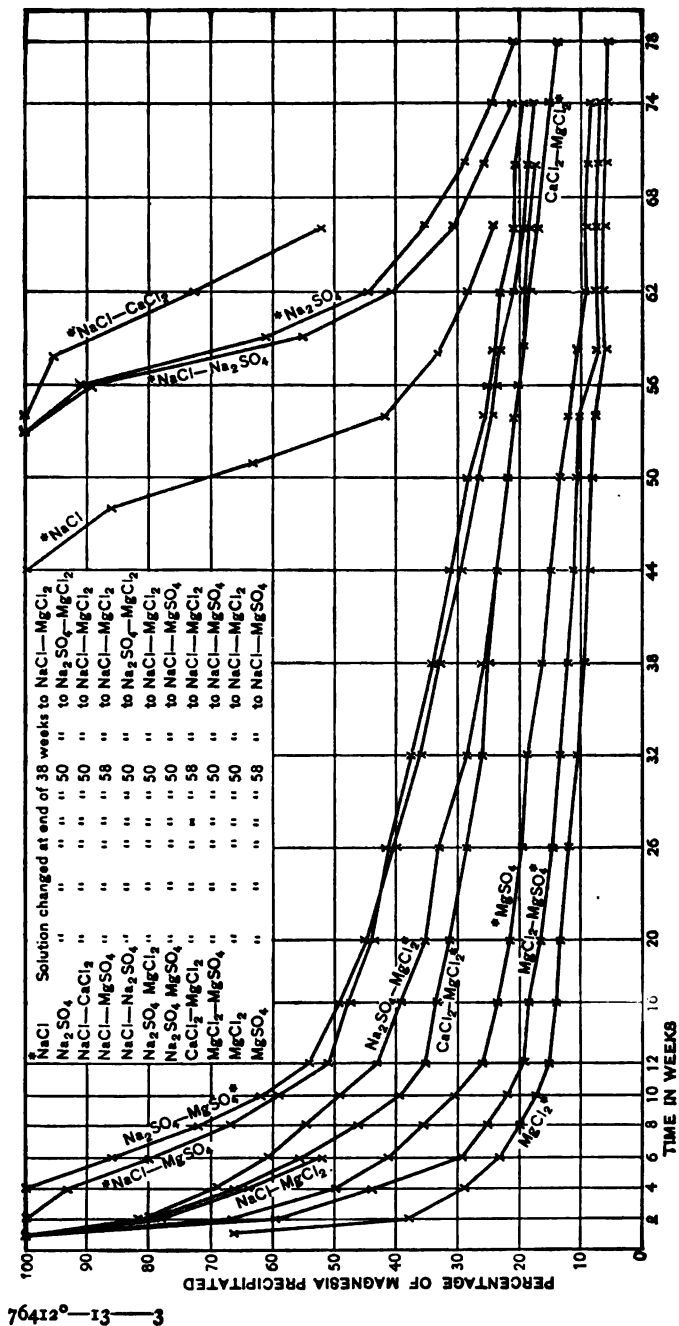


Fig. 8.—Percentage of magnesium precipitated by the unset cement from the various solutions.

culations it was assumed that no chlorine, sodium oxide, silica, iron, or alumina was absorbed or in any way removed from the solution or cement, excepting the sodium carbonate series. In preparing the residue for analysis, after the removal of the last solution as completely as possible, there was usually remaining from 50 to 100 grams. The residue plus the remaining solution was weighed and then evaporated at 103° to constant weight in a current of air free from carbon dioxide. Thus it is seen that no attempt was made to remove, by washing out with pure water, the solution remaining on the residue. This would also have removed some of the other material than the salts in the solution. But as the weight and composition of this latter was known, it was a

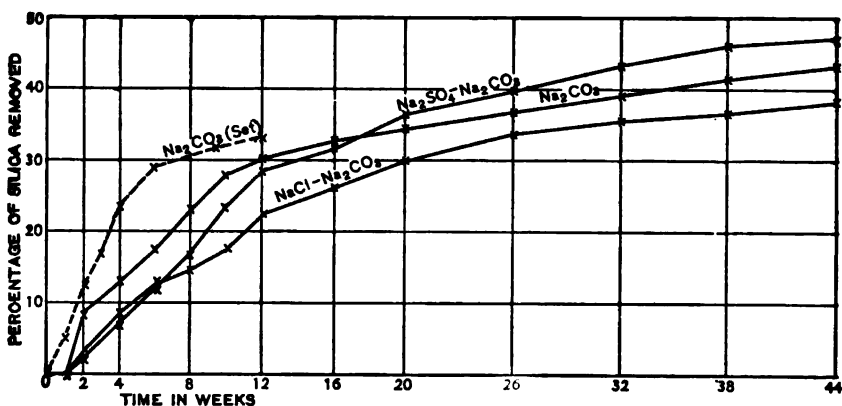


Fig. 9.—Percentage of silica removed by the solution sodium carbonate, using set and unset cement.

simple matter to determine the percentage of salts on the residue from this source. Therefore, in the "calculated" residue (Table 4, p. 109) there appears chlorine, although, as mentioned above, it was assumed that none was removed from solution. The chlorine percentage shown in the column "calculated" residue is therefore the chlorine which was present in the solution remaining on the residue.

In general, there is a remarkable agreement between the composition of the "calculated" and "analyzed" residue, when one considers the number of analyses upon which the former depends. It does seem in several cases as if some alumina had been lost by

the cement, and also sodium and potassium oxide. Also apparently some chlorine was gained. This is shown in the tables by the fact that the silica and alumina percentages in the column marked "Calculated" residue are higher than in the column marked "Analyzed," and the reverse in the case of the chlorine. The increase in the chlorine content has been noted by others, as mentioned in the first part of this paper. Lately also Poirson⁸ has called attention to the fact of the formation of chloro-aluminates of lime.

He has also prepared this in a number of ways and gives as a formula $2(\text{Al}_2\text{O}_3, 3\text{CaO}) \text{CaCl}_2$. Candlot⁹ has also prepared this calcium chloro-aluminate. It is unstable in pure water, and according to Poirson also in solutions of sulphates, when it is decomposed with the formation of calcium sulpho-aluminate.

Carbon dioxide was gained. This was unavoidable unless particular precautions had been taken, as the solutions and residue came into contact with the air during removals and additions. In the solutions containing sodium carbonate silica was removed in notable quantities and was necessarily taken into consideration in the calculations.

(d) CHANGES IN SULPHURIC ANHYDRIDE CONTENT

The results obtained from the determination of the SO_3 radical present in the solution when removed from the cement, as shown in Fig. 10, were possibly the most important obtained, especially in the light of the universally accepted theory of the cause of the destruction of cement in the presence of soluble sulphate. As stated before, it is generally accepted in such cases that the lime and alumina of the cement combine with the sulphate radical to form a so-called calcium sulpho-aluminate which has the formula $\text{Al}_2\text{O}_3, 3\text{CaO}, 3\text{CaSO}_4 + \text{H}_2\text{O}$, the amount of water being given even as high as 69 molecules.

The belief in the formation and existence of such a compound is due largely to the widely read works of Le Chatelier, Michaelis, and Candlot. Candlot has made this material by the reaction

⁸ *Le Ciment*, Pts. 6 and 7, 1910 (through *Zs. für Ch. und Anal. Zement*, p. 151).

⁹ *Ciment et Chaux Hydrauliques*.

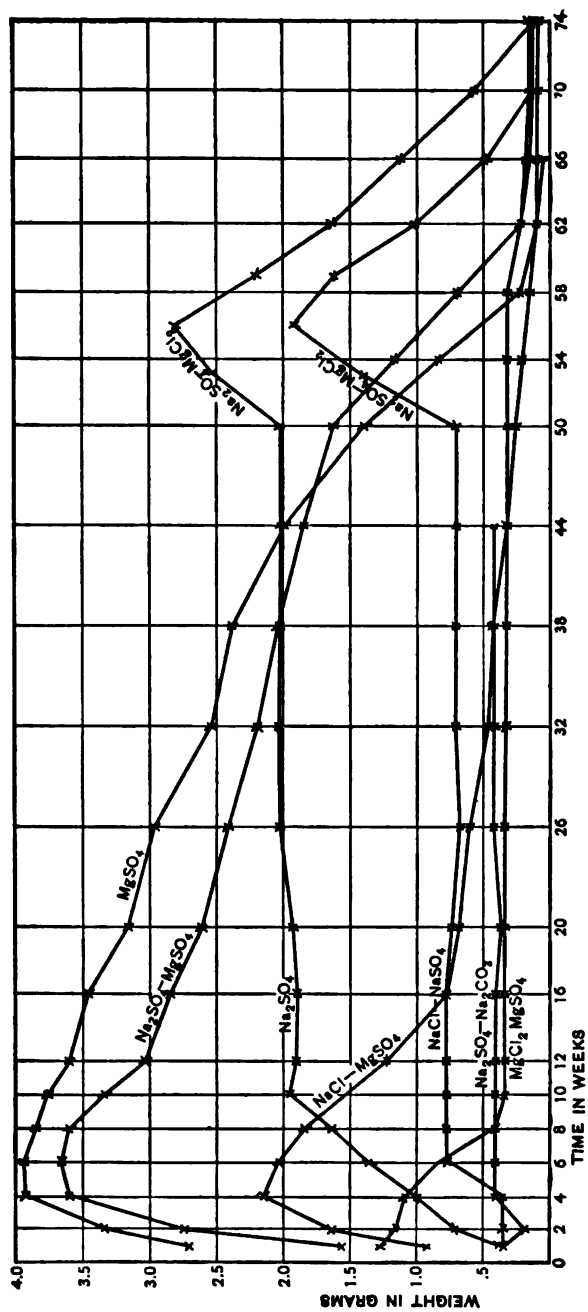


Fig. 10.—Weight of subphuric anhydride precipitated or dissolved by various solutions in contact with the unset cement.

between sulphate of lime and aluminate of lime (which aluminate he does not mention). He obtained in this way a compound analyzing $\text{Al}_2\text{O}_3, 3\text{CaO}, 2.5\text{CaSO}_4$. Deval¹⁰ also made a compound, analyzing $\text{Al}_2\text{O}_3, 3\text{CaO}, 3\text{CaSO}_4, 28.5\text{H}_2\text{O}$ from sulphate of aluminum, lime water, and sulphate of lime, and also from the reaction of calcium sulphate and tricalcium aluminate. Later, Deval¹¹ using sodium sulphate has found that some of these calcium sulpho-aluminates contained more sulphate of lime and others less than the amount necessary to form the above-mentioned compound. He therefore rejects his first formula, and after substituting a second, suggests that it is of indefinite composition, depending on various factors such as the SO_3 concentration, percentage of Al_2O_3 present and the ready availability of the lime reacting. Klinkenberg¹² prepared sulpho-aluminates from dicalcium aluminate and sulphate of lime, having the following compositions: $\text{Al}_2\text{O}_3, 2\text{CaO}, 3\text{CaSO}_4, 19.5\text{H}_2\text{O}$; $\text{Al}_2\text{O}_3, 2\text{CaO}, 2\text{CaSO}_4, 18.3\text{H}_2\text{O}$; $\text{Al}_2\text{O}_3, 2\text{CaO}, \text{CaSO}_4, 12.5\text{H}_2\text{O}$. Rebuffat¹³ concludes that for cement in sea water the formation of sulpho-aluminate is at most transient and can take place only to a small extent, and therefore sulpho-aluminates have a very slight action on the stability of cement. They are also attacked strongly by sodium chloride, small amounts of alumina, and large amounts of lime and SO_3 going into solution.

The destructive qualities of this substance are alleged to be due to its crystallization with such a large content of water, the crystals occupying a very much larger space than the alumina and lime from which they are formed. Moreover, by extracting the lime and alumina and preventing this normal crystallization or gelatinization (depending upon whether they would have formed normal crystals or colloids) the normal setting and hardening phenomena are completely interfered with, the result being a soft crystalline nonhardening mass.

An examination of the diagram showing the amounts of SO_3 removed at the various periods will show the impossibility of this formula. The cement used contained 8.44 per cent Al_2O_3 . In the experiments 10 grams of cement or 0.844 gram of alumina

¹⁰ Bull. Soc. D'Encourag., p. 49; 1900.

¹¹ Bull. Soc. D'Encourag., p. 785; 1901.

¹² Dinglers Poly. J., pp. 89, 114, 137, 163; 1894.

¹³ Chem. Zentral., p. 1927; 1901.

were present. The amount of SO_3 necessary for this amount of Al_2O_3 in order to form the tricalcium sulpho-aluminate is 1.98 grams, but in the case of the sodium chloride-magnesium sulphate solution we find at the end of the fourth week that 2.16 grams SO_3 have been removed. In the case of the sodium sulphate solution, at the end of the twenty-sixth week 1.96 grams were removed, and this increased to 2.86 grams at the end of the fifty-sixth week. In the case of the sodium sulphate-magnesium sulphate and magnesium sulphate solutions the results are still more striking. In the former case from the second to the end of the thirty-eighth week more SO_3 had been removed than there was alumina to satisfy it; in the latter case the same applies from the start to the end of the forty-fourth week. In this latter solution, when we have the maximum precipitation of 3.94 grams SO_3 at the end of the sixth week, there would be required 1.67 grams Al_2O_3 , almost twice the amount actually present.

Where the lime was removed from the cement it is also noticeable that there is not a sufficient amount of it left to form with the SO_3 removed from the solution tricalcium sulpho-aluminate. In the case of the solution magnesium sulphate just cited we have 2 grams of SO_3 present in the cement at the end of the forty-fourth week. This requires 2.8 grams of lime, but we find that 4.24 grams have been removed from the cement, leaving 2.14 grams, which is 0.66 gram less than the amount required. These results would indicate that tricalcium sulpho-aluminate can not be formed, and therefore disintegration can not result from this cause.

Several investigators have noticed that compounds of iron and lime swell and form other compounds in the presence of sulphate of lime. Their statements, however, in respect to this compound are not as positive as in regard to sulpho-aluminate.¹⁴

This theory was offered before the present advance in colloid chemistry had been made and before it had been generally accepted that the hydration of cement was a colloidal formation. When the property of colloids to absorb ions is remembered, the inability to obtain a definite compound and the high amounts of

¹⁴ Poirson, *Zs. für Ch. und Anal. Hydraul. Zemente*, 1, pp. 151-159. Michaelis, *Bul. Soc. D'Éac.*, p. 818; 1897. Schott, *Tonind. Zs.*, 18, p. 819.

sulphuric anhydride removed from solution in the present experiments is readily explained. By referring to the figures it is also noticed that the greater amounts were removed when the solutions used contained magnesium sulphate and where also large amounts of the magnesium hydrate gels were formed, and consequently there are more colloids present to absorb the sulphate radical.

As colloid absorption depends, among other things, upon the concentration of the solution and the presence of other ions in this solution, one would expect in the present instance that where the lime content of the successive solutions was gradually decreased there would be a possibility of the absorbed radical being given up, and such is found to be the case, as reference to the figure shows.

When chloride was present with the sulphate it is readily seen that the amount of sulphate formed is less than when the chloride was absent. Thus, the maximum amount removed from the sodium sulphate solution was 1.96 grams, and when sodium chloride was present this amounted to but 0.78 gram; with magnesium chloride it amounted to 1.13 grams. When magnesium sulphate alone was used the maximum reached 3.94 grams. When sodium chloride was present with this salt it reached but 2.16 grams, and with sodium chloride it reached but 1.26 grams. It is quite evident from these results that the chloride increased to a considerable extent the solubility of the sulphate which was formed. This has been noticed by others in a number of instances, especially in the analyses of samples of concrete which have been exposed to the action of sea water. The difference between the SO_3 content of the exterior and interior of the concrete varies but slightly.

Attempts were made to prepare this tricalcium sulpho-aluminate in a number of ways, using calcium aluminates made from pure lime and alumina and fusing them in the arc in such a proportion as to give $\text{CaO}.\text{Al}_2\text{O}_3$; $2\text{CaO}.\text{Al}_2\text{O}_3$; and $3\text{CaO}.\text{Al}_2\text{O}_3$. About 3 grams of each of these were then shaken with a solution of sodium sulphate until no further swelling was observed. The action of the sulphate on these three aluminates was very different.

With all there was an almost instantaneous setting, notwithstanding the solutions were vigorously shaken in closed flasks. But with the monocalcium aluminate there was little swelling, even after three weeks, during which it was frequently shaken. With the dicalcium aluminate swelling started within 24 hours and increased to such an extent at the end of two weeks that, after standing 24 hours without shaking, the mass occupied about 250 cc. The swelling with the tricalcium aluminate was more rapid and to a greater extent, the mass occupying about one-half a liter. After there was no further increase in volume the material was filtered off and washed with lime water, air being excluded, until all the SO_3 was absent from the filtrate, and then with 80 per cent alcohol until the filtrate showed no lime. From the analysis of the residue the radicals were found to be present in the following molecular ratios:

	From $\text{CaO} \cdot \text{Al}_2\text{O}_3$	From $2\text{CaO} \cdot \text{Al}_2\text{O}_3$	From $3\text{CaO} \cdot \text{Al}_2\text{O}_3$
Al_2O_3	1.0	1.0	1.0
CaO	1.06	3.33	2.49
CaSO_4.....	.43	1.54	1.31

This was then repeated, with the exception that the material was filtered from time to time and the residue treated with a fresh portion of sodium sulphate. This was done as it had been noticed that the solution contained large quantities of alumina and traces of lime. This treatment was then continued until alumina no longer appeared in the solution. The residue then gave:

	From $2\text{CaO} \cdot \text{Al}_2\text{O}_3$	From $3\text{CaO} \cdot \text{Al}_2\text{O}_3$
Al_2O_3	1.00	1.00
CaO	2.35	2.46
CaSO_4	2.06	3.27

The above was then repeated, using a solution of plaster of Paris, removing a part of the solution from time to time and

quantitatively determining when there was no further change in the SO_3 content. Here also alumina appeared in the solution at first. There was obtained in this case:

	From $2\text{CaO} \cdot \text{Al}_2\text{O}_3$	From $3\text{CaO} \cdot \text{Al}_2\text{O}_3$
Al_2O_3	1.0	1.0
CaO	2.79	4.96
CaSO_4.....	.87	1.82

Finally, the aluminates and plaster were placed together in a flask and shaken and more powdered plaster of Paris added from time to time until alumina no longer appeared in the solution, but until the SO_3 and lime content apparently were constant. The molecular ratios were then:

	From $\text{CaO} \cdot \text{Al}_2\text{O}_3$	From $2\text{CaO} \cdot \text{Al}_2\text{O}_3$	From $3\text{CaO} \cdot \text{Al}_2\text{O}_3$	
			No. 1	No. 2
Al_2O_3	1.0	1.0	1.0	1.0
CaO	1.73	2.9	3.11	2.98
CaSO_4	1.17	1.9	2.5	2.65

It is apparent from these results that even under favorable conditions it is impossible to obtain a compound of the formula $3\text{CaO} \cdot 3\text{CaSO}_4 \cdot \text{Al}_2\text{O}_3$, but in the last experiment, using the tricalcium aluminate and powdered plaster, there was obtained a product approaching very closely Deval and Rebuffat's formula of $3\text{CaO} \cdot 2.5\text{CaSO}_4 \cdot \text{Al}_2\text{O}_3$. It was impossible to secure anything approaching this formula with the compound $\text{CaO} \cdot \text{Al}_2\text{O}_3$, or the mixture $2\text{CaO} \cdot \text{Al}_2\text{O}_3$; or by using sodium sulphate with any of these. Also it was found that the sodium did not in any case form a sodium calcium sulphoaluminate.

Lime and silica were fused in the arc in the ratio of $2\text{CaO} \cdot \text{SiO}_2$, and $3\text{CaO} \cdot \text{SiO}_2$, and treated in the same manner with sodium sulphate and plaster, but there was no evidence of the formation of a sulphosilicate.

2. ACTION OF SOLUTIONS ON SET CEMENTS

The results obtained with the set cements were very striking. As noted before, the action was very much more vigorous in this case, as is shown in Table V, where the amount of lime removed in the two cases is shown at as nearly corresponding periods as possible. (See also Table p. 107.)

This is also shown in the Figs. 11 to 13. This more vigorous action is due to the fact that in the set cements a considerable

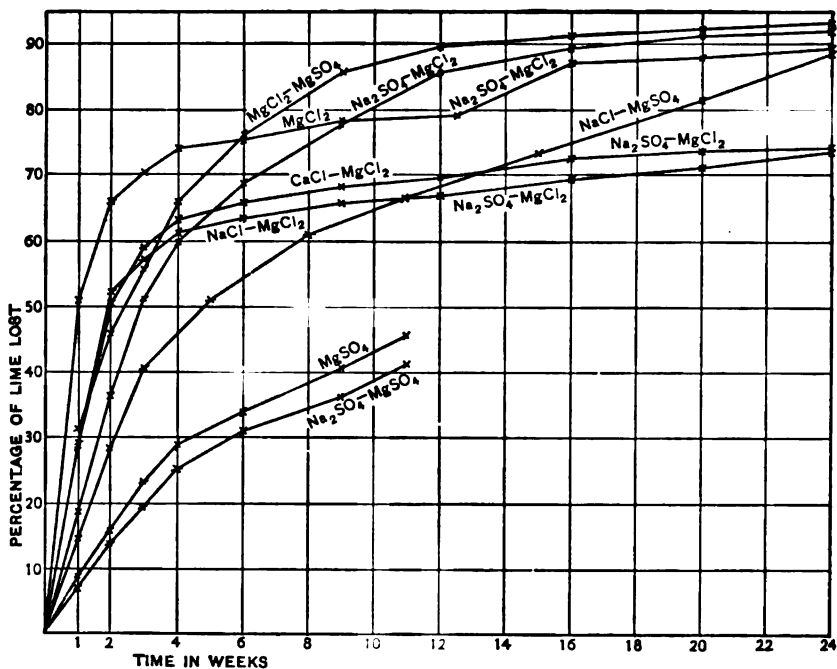


Fig. 11.—Percentage of lime lost by the set cement to solutions of various salts

part of the lime is already in the hydrated state. With the unset cement there was a decided tendency for the lime in a particle in reacting to go into solution and throw the insoluble products resulting from its reaction with the solution over the remainder of the particle of cement. When the solution was changed so that this insoluble product was more soluble, the decomposition started in again very vigorously, as shown. With the "set" cement (by setting twice with an intermediate grinding

and a final grinding, so that the material all passed a 200-mesh sieve) the lime hydrate was distributed uniformly through the mass and tended to go into solution more uniformly and rapidly.

While the rate of action as a whole was greater in this series than when the fresh cement was used, yet the solutions did not retain their relative positions as regards destructive power; thus, the solution calcium chloride-magnesium chloride, one of the most

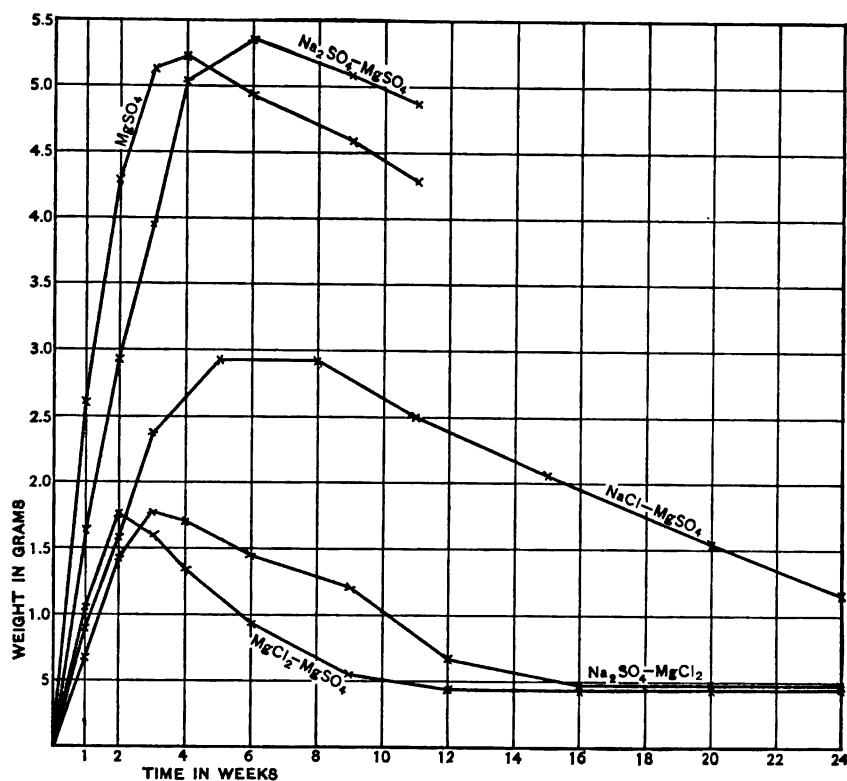


Fig. 12.—Weight of sulphuric anhydride precipitated or dissolved by various salts in contact with the set cement

active in the first series, as shown in Figs. 1 to 5, in the present series removed 74.1 per cent in 24 weeks and 86.4 per cent in 78 weeks in the first series, while the magnesium chloride-magnesium sulphate solution in the present series removed 93.3 per cent in 24 weeks and 74.9 per cent in 74 weeks in the first series. Other similar cases are noticeable from the table.

The solutions sodium sulphate-magnesium sulphate and sodium sulphate were removed from the cement and the tests discontinued when it was noticed that the sulphuric anhydride was no longer being removed from the solution, but that which had been removed was redissolving. This was done in order to separate the sulphate formed by heavy solutions and to obtain an analysis of the sulphate in the pure state. It was found, however, that such separation was not successful.

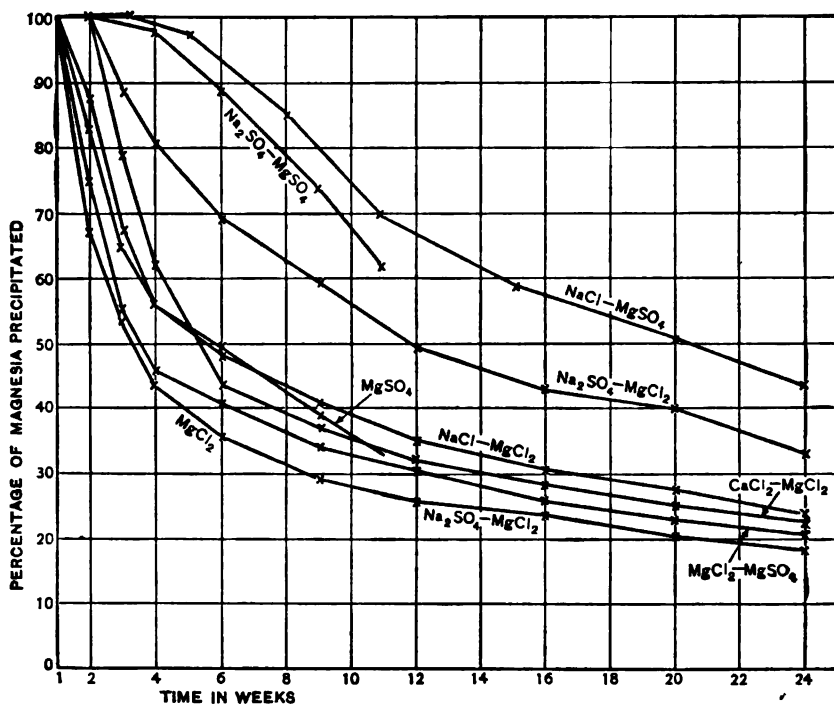


Fig. 13.—Percentage of magnesia precipitated by the set cement from various solutions

In this series the effect of the changing of one of the salts in the solution after the rate of solution had decreased is not as marked as with the unset cement. This would result largely because the previous action before the change had been much more marked than with unset cement.

The results in this series, as shown in the tables and figures, do not need any further discussion beyond what has been said when discussing the unset cement, the same general effects of the solutions being noticeable in both cases.

V. ACTION OF SEA WATER ON VARIOUS FRESH AND SET CEMENTS

Some tests very similar to the preceding were inaugurated at the laboratory at Atlantic City when work at that laboratory was first started. The starting of these tests also antedated preceding ones, so that they are not quite similar, since certain results were obtained which made changes advisable in any later work of a similar character. Thus, at Atlantic City, there were used 100 grams of cement and 2000 cc of sea water, this large amount of cement being used to avoid the swelling which has been so frequently noted when cement is shaken with large quantities of water. With this amount the action was continued so long that in later tests the amount of cement was decreased one-half, using 50 grams to 2000 cc, which compares better with the ratio in the preceding tests of 10 grams to 500 cc.

Since at Atlantic City there was no particular interest in solutions other than sea water, it was deemed advisable to use a number of different cements in order to make the series more comprehensive, and also to compare these results with results obtained by the use of distilled water. The quantities and kinds of cements used and kinds of water are:

	Grams in 2000 cc sea water.
No. 4, German iron-ore cement.....	100
No. 5, normal Portland.....	100
No. 23, Portland, low SO ₃	100
No. 24, slag cement.....	100
No. 24-b, slag cement.....	50
No. 25, natural cement high in MgO.....	100
No. 30, white Portland cement.....	100
No. 47, mixture of 12 Portland cements.....	50
No. 52, natural cement, low MgO.....	50
No. 53, Boulougne Sur Mer Cement.....	50
	Grams in 2000 cc distilled water.
No. 24-b, slag cement.....	50
No. 47, mixture of 12 Portland cements.....	50
No. 52, natural cement, low MgO.....	50
No. 53, Boulougne Sur Mer Cement.....	50

Also duplicate tests were conducted using set samples of all but Nos. 23 and 30, in both sea and distilled water. These cements were set by gauging with water and placing in the steam in a

water bath, drying, grinding, and resetting. It will be noticed from the analyses of these (Tables 7 and 8, p. 111) that large amounts of carbon dioxide were absorbed so that the method of setting in the preceding tests was changed, as noted. In the case of Nos. 4, 5, 24, and 25 no samples of the set cements were received for analysis, so that comparison between the calculated residues and analyzed residues is impossible. With the other cements these were made and are given in the tables; also in the Figs. 14 to 16 the percentage of lime removed is calculated on the per cent of lime present, other than as carbonate. This was done as it was assumed that the carbonate is inert toward the waters. It will be noted that the percentage of lime removed, when calculated in this manner, approaches much more closely to the percentage removed in the unset cement series. It should be borne in mind that the carbonate also acts to prevent solution of the lime otherwise combined, as it envelops the particles of cement and prevents the solution from reaching it. That the lime removed from the set cement appears less than that removed from the unset, contrary to the tests in the first part of this paper, can be explained readily by this preservative action. In the set cement used in these tests the carbon dioxide amounted to but 1.98 per cent, while in the present cases it amounts to as much as 14.19 per cent.

In general, the results obtained from the different tests do not show as much as was expected. In the sea water the Portland cements, including the "iron ore" but excluding the white cement, act very similarly. It is probable that the manner of manufacture enters into the question here. To produce a sound white cement would require a higher temperature of burning than in the case of the manufacture of the ordinary lower alumina cements. Also a sound iron oxide cement could be made at a lower temperature than a cement of ordinary composition. So that while a high iron oxide and high alumina and an ordinary cement might show much different action when burned at the same temperature yet they could be very similar when burned at the temperature just required for clinkering. The white cement enters into solution very slowly, finally showing the least solubility of the

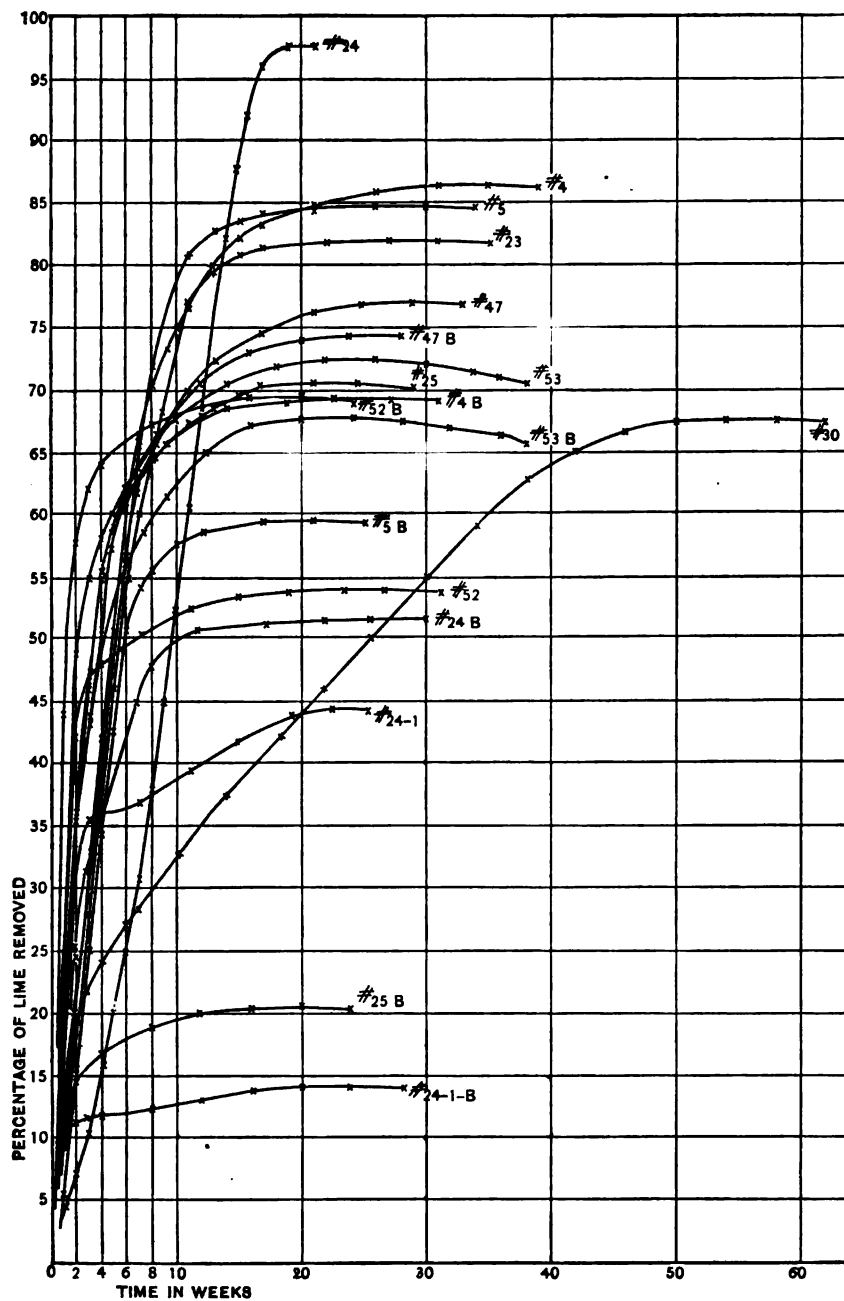


Fig. 14.—Percentage of lime removed from various set and unset cements by sea water.
B=set cement

clinkered cements. This is contrary to the accepted idea and theory, the aluminates being supposedly more soluble than the silicates or ferrites. The two samples of No. 24 acted very differently. In the first test twice as much cement was used as in the second one, hence it would be expected that, other things being equal, the solvent effect would be greater, but the results show the opposite. Also it would be expected that if there was any swelling it would be greater with the less amount, but here again the tests show the opposite. In view of the fact that it is

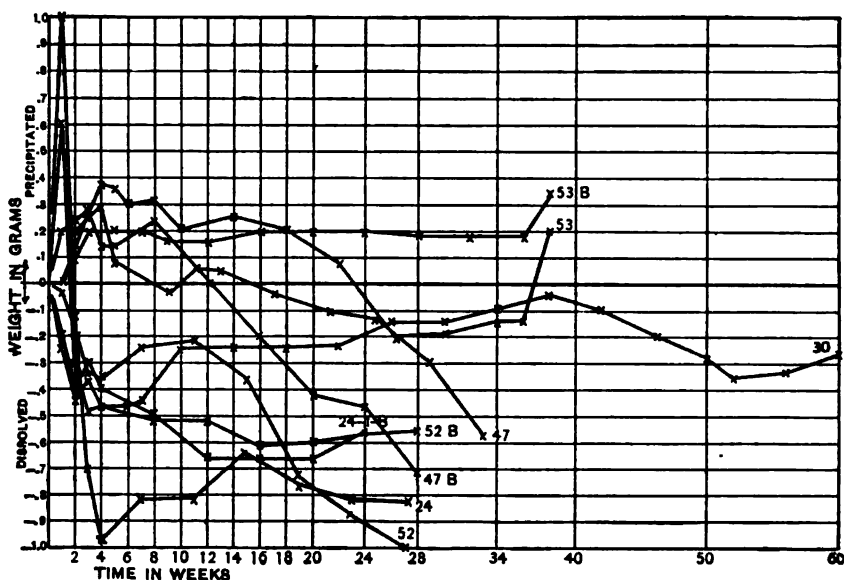


Fig. 15.—Weight of sulphuric anhydride precipitated or dissolved by sea water in contact with various cements. B=set cement

a slag cement and the two samples represent two different shipments and show different composition it is more reasonable to conclude that the different results are due to a difference in the constitution of the material.

The treatment with distilled water was carried on to show the greater solubility in the sea water, caused by the presence of the various salts. A comparison of the results obtained in the two series shows how decidedly the solubility has been increased. It does not show, however, which of the salts has caused this action.

It was for this reason that the tests in the first part of this paper were conducted (cement No. 23 was the one used there) and there was shown the increased solvent power of the chlorides over the sulphates and of magnesium chloride over sodium chloride.

The results of the absorption of the sulphuric anhydride are similar to those obtained previously. At first the sea water loses this radical to the cement, but when the lime concentration falls

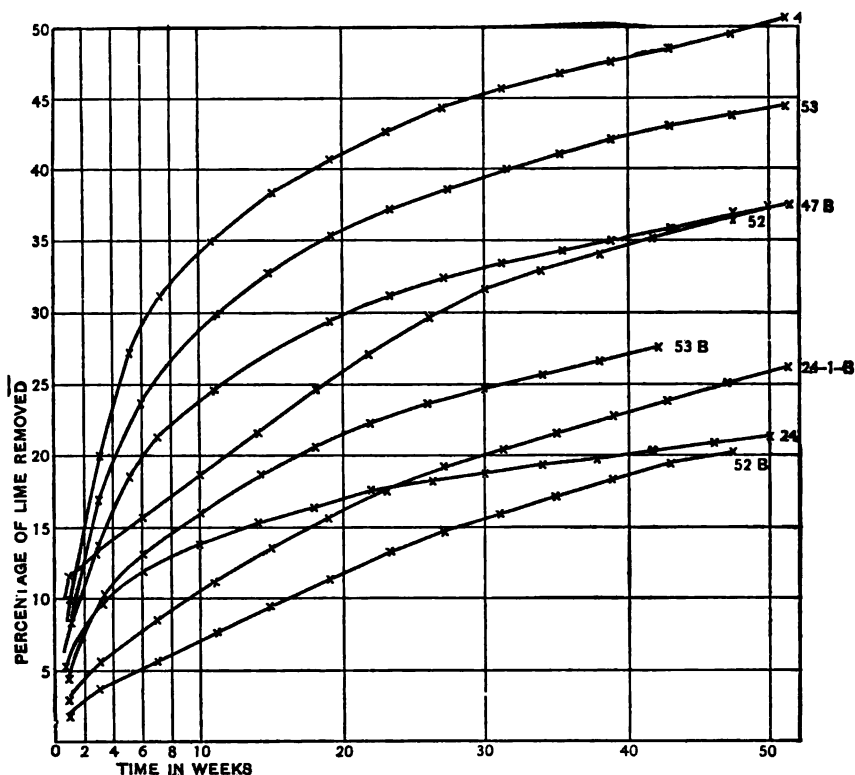


Fig. 16.—Percentage of lime removed from various cements by distilled water.
B=set cement

below 0.10 to 0.15 grams per liter it returns into solution. This explains some of the variations in the figure. When it was noticed that the amount of lime in the water removed was falling off considerably, the time of contact was increased with consequent increase in lime concentration and increased absorption of the sulphuric anhydride by the cement.

The liberation of lime being coincident with the absorption of sulphuric anhydride slow hardening cements would absorb less SO_3 than quick-hardening ones. This is contradicted by the white cement which is slow hardening and by the Boulougne Sur Mer cement which contained originally less sulphuric anhydride than any of the rest and which retained the most.¹⁵

The slag cements contain some sulphide of lime. This was not completely oxidized during these experiments, either with the sea or distilled water tests.

The distilled water series did not show any sulphuric anhydride removed from the cement. The plaster added for retarding the set was apparently fixed in some manner and not dissolved.

The amount of magnesia removed depended entirely upon the lime lost. Several cements, when the tests had been carried on for a considerable time, show the removal of lime and sulphuric anhydride from the sea water, after apparent equilibrium had been reached; but this occurred only when there was neither of these available in the cement for solution and when the large amounts of hydro gels formed readily absorbed them from the water.

The analysis of the residue shows that there was but little chlorine or sodium removed from solution, entirely too small an amount to form conclusions as to the existence of any definite compound. The percentages of oxide of sodium, chlorine, magnesia, and sulphuric anhydride given in the horizontal columns marked "analyzed" include the per cent of the radical in the sea water on the filtered unwashed residues. These latter percentages are given in the last vertical column.

There are no breaks in the curves that might have shown that the lime of the silicates or alumina or ferrites has a different solubility.

The behavior of the iron ore cement is not different from the other Portland cements so far as the removal of lime is concerned. Gaines¹⁶ has noted that while the iron ore cements might be less readily affected by sulphated waters, yet they are as readily affected by chloride of lime or magnesia as the ordinary cements.

¹⁵ Le Chatelier, *Chem. Zentralblatt.*, 15, p. 451.

¹⁶ Brick, June, 1910.



Fig. 17.—*Laboratory at Atlantic City, N. J.*



Fig. 18.—*Cast-iron cylinder mold*

PART II

VI. FIELD INVESTIGATION

It was thought desirable to study the effect of sea water on cements and concretes when exposed under actual service conditions. While much valuable information can be obtained from an inspection of existing concrete structures in sea water, it is practically impossible to obtain reliable and complete information after a structure is several years old as to the qualities of the materials used and the character of the workmanship in construction. The field laboratory was located at Atlantic City, N. J., as it was readily accessible and the sea water at this point was rather pure and undiluted from fresh-water streams. Atlantic City is situated about 150 miles south of New York on an island 7 miles long and from $\frac{1}{8}$ to 1 mile in width, lying about 6 miles from the New Jersey mainland, with bays and salt marshes between. The building used as a laboratory (see Fig. 17), under which the exposure tests were made, was located on a pier 700 feet from shore, about 20 feet above mean tide with 20 feet depth of water beneath.

Concrete of varied composition was made with Portland, natural, slag, and other special sea-water cements under conditions approaching as closely as possible the various methods used in sea-water construction. Several thousand briquettes and other small test pieces were made and exposed to sea water in connection with the concrete tests for the purpose of comparing various types and brands of cements.

VII. OUTLINE OF TESTS

Series I.—To determine the effect of sea water on normal Portland cement concrete, 8 by 16 inch cylindrical test pieces were made and exposed to sea water both between tides and below

low tide. The concrete was placed in various ways and various mixtures were used.

Test number	1 part Portland cement to parts —		Concrete placed in molds	Exposed to sea water	Tested for compressive strength at following periods:							
	Sand (Jersey)	Stone			Weeks			Years				
					4	13	26	1	2	3	5	
*1	2	4 trap rock	Through tremie	Immediately	3	3	3	3	3	3	3	
*2	2	do.....	Above water.....	do.....	3	3	3	3				
*3	2	do.....	do.....	In 24 hours.....	3	3	3	3				
4	2	do.....	do.....	In 3 days.....	3	3	3					
5	2	do.....	do.....	In 7 days.....	3	3	3					
6	2	do.....	do.....	In 4 weeks.....	3	3	3	3				
*7	2	do.....	do.....	In 8 weeks.....	3	3	3	3	3	3	3	
8	2	do.....	do.....	Between tides, in 8 weeks.	3	3	3	3	3	3	3	
*9	3	6 trap rock	Through tremie	Immediately	3	3	3	3	3			
*10	3	do.....	Above water.....	In 8 weeks.....		3	3	3	3			
*11	3	6 Jersey gravel...	Through tremie...	Immediately.....	3	3	3	3	3			
*12	3	do.....	Above water.....	In 8 weeks.....		3	3	3	3			
*13	4	8 trap rock.....	do.....	do.....	3	3	3	3	3	3	3	
14	4	do.....	do.....	Between tides, in 8 weeks.	3	3	3	3	3	3	3	

* Duplicate test pieces were made and placed in fresh water in a similar manner.

To determine the effect of sea water on concretes made with slag, natural, and other special sea-water cements, 8 by 16 inch cylindrical test pieces were made of concrete in the proportion of 1 part cement to 2 parts of Jersey sand and 4 parts of trap rock by volume. They were stored in a damp room for 8 weeks when they were immersed in sea water to remain until tested. A duplicate set was made and placed in fresh water. Three test pieces were tested for compressive strength at the end of 13 and 26 weeks and 1 and 2 years.

Series 2.—Tension briquettes were made of all of the cements collected, which after storage for 24 hours in moist air were placed in sea water and tested at periods ranging from 4 weeks to 2 years. A duplicate set of briquettes was also placed in fresh water and tested at the same periods.

Series 3.—Plaster of Paris was added in percentages varying from 0.05 to 20.0 to a normal Portland, a high-iron Portland, a

slag, and a natural cement, which were tested in briquette form as in series 2.

Series 4.—Briquettes were made of mortar in the proportion of 3 parts standard Ottawa sand to 1 part each of Portland, slag, and natural cements, which were stored in moist air for 24 hours and then placed in a 10 per cent solution of ammonium carbonate for 6 days, after which part were placed in fresh water and part in sea water and tested at periods ranging from 4 weeks to 2 years.

Series 5.—Both neat and mortar briquettes were made, using standard Ottawa sand and Portland, slag, and natural cements, which were mixed with 1, 5, and 10 per cent solutions of ammonium carbonate in place of clear water. After 24 hours' storage in moist air part were placed in sea water and part in fresh water to be tested at periods ranging from four weeks to two years.

Series 6.—Two neat cement pats 3 inches in diameter, one-half inch thick at the center, and tapering to a thin edge were made of all cements used in series 2 and 3 above. One was stored in fresh water and the other in sea water, where they were observed from time to time and their condition noted.

VIII. PROPERTIES OF MATERIALS USED

1. CHEMICAL ANALYSES

The chemical analyses of the various cements, limes, plaster, and sand used are given in Table 9, p. 115.

2. PHYSICAL ANALYSES

The results of physical tests of various cements are given in Table 10, p. 117. The results of the physical analyses of the sands and stones used are as follows:

	Jersey sand	Seashore sand	Meramec sand	Jersey gravel	Meramec gravel	Gorgona gravel	Trap rock
Weight per cubic foot, in pounds.	86.52	85.92	100.6	93.59	102.4	*121.49	91.01
Fineness, per cent pass sieves:							
200.....	0.95	2.45	0.20	0.88	0	1.80	0.50
100.....	7.91	44.95	1.30	1.41	0	3.52	.80
80.....	12.09	64.15	3.60	1.73	0	5.22	.93
50.....	41.86	98.85	13.90	2.26	0	9.93	1.14

* The weight per cubic foot of Gorgona gravel passing the one-fourth inch sieve is 109.05 pound, and of that retained on the one-fourth inch sieve 112.38 pounds.

	Jersey sand	Seashore sand	Meramec sand	Jersey gravel	Meramec gravel	Gorgens gravel	Trap rock
Fineness, per cent pass sieve— Continued.							
40.....	56.11	99.40	37.00	2.51	0	13.37	1.24
30.....	73.43	99.50	64.00	2.78	0	18.08	1.34
20.....	82.69	99.60	81.50	3.04	0	22.63	1.42
10.....	93.13	99.70	97.00	3.49	.95	29.12	1.57
6.....				4.19		36.90	1.93
4.....	100.00	100.00	100.00	7.88	43.00	48.30	3.38
2.....				40.13	79.30	67.69	26.06
1.....				80.50	92.20	82.46	79.81
1.....				91.94	98.50	88.12	97.19
1½.....				99.63	100.00	95.22	100.00
1½.....				100.00		97.94	
1½.....						100.00	

IX. PREPARATION OF TEST SPECIMENS

1. CONCRETE TEST PIECES

(a) PROPORTIONING

The ratios of the constituent materials of the concrete were assumed according to volume measure, as is done in practice, but it was deemed advisable to transpose the volume measurements into weight measurements, as the actual quantity of sand or stone in a given volume is largely dependent upon its state of dryness and the method employed in filling the measure.

The weight per cubic foot of all cements used was assumed as 100 pounds, and the weights per cubic foot of the sand and stones used are reported elsewhere in this paper.

(b) CONSISTENCY

Only one consistency was used for all concrete. It has been termed a "wet" consistency and may be defined as follows: The consistency is such that the concrete contained all the water possible without being creamy or watery. It might be termed a quaking or mushy consistency and became very mushy when tamped. The quantity of water required was predetermined for each kind of concrete, and the same percentage of water was used for making all similar test pieces.

(c) **MIXING**

Material sufficient for making 3, 6, 9, or 12 cylinders was mixed at one batch, depending upon the test. The materials were mixed by shovel on a concrete floor in the following manner: The stone, sand, and cement were spread on the floor in successive layers, and the dry materials were thoroughly mixed by turning over twice with shovels. After this dry mixing the materials were again spread out onto the floor and a crater formed in the center. The required water was weighed and poured into the crater, the material on the outer edge being turned into the crater with a shovel. After the water was absorbed the materials were turned over three times, resulting in a uniform and homogeneous mixture.

(d) **MOLDING**

The concrete test pieces were made in the shape of cylinders or short columns, 8 inches in diameter and 16 inches in length. They were molded in cast-iron molds the inside surfaces of which were machined and the molds made removable in three sections held together by clamp screws and wedges as shown in Fig. 18.

The concrete was tamped into the molds with a 12-pound $\frac{3}{4}$ by $3\frac{1}{2}$ inch peen-shaped tamper. About one-quarter of the height of the mold was filled and tamped at one time, the tamper being lifted to the same height each time and moved systematically, covering the entire surface twice with the tamper at each filling. The top surface was troweled level with a plasterer's trowel.

Where test pieces were molded in submerged molds the concrete was placed through a tremie or pipe. The pipe was 30 inches in length and 5 inches in diameter. A cloth was placed over the bottom of the pipe, the pipe was filled with concrete to a depth of about 25 inches, and was immersed until the bottom of the pipe rested on the bottom of the mold, when the cloth was withdrawn from the bottom of the pipe. The pipe was then gently raised from the bottom a little at a time, the concrete flowing from the pipe, which was being continually supplied with concrete so that the level of the concrete in the pipe was always above the level of the water. This was continued until the mold was full, when the concrete was allowed to overflow slightly and the top was somewhat leveled with a plasterer's trowel. After making several series of

tests it was found that the same results could be had by filling the molds with sea water, drawing them above the surface of the ocean, placing the pipe as before through the water to the bottom of the mold, and immersing the mold again immediately after filling. This made it easier to handle and fill.

(c) STORAGE

The concrete test pieces were stored in various ways after molding in accordance with the program of tests. Those made in submerged molds were taken from the water after three or four days, removed from the molds, and placed in crates, as illustrated in Fig. 19. The test pieces made in fresh water for comparative purposes were also stored in fresh water. Where the concrete was immersed immediately after being placed, the molds were taken off after three or four days and the test pieces placed in crates and suspended in the sea. All test pieces which were aged for periods varying from 24 hours to 8 weeks were stored in a moist room during this time. Twenty-four hours after molding the molds were removed from the test pieces, which were sprinkled each day to keep them from drying until they were immersed either in fresh water or in the ocean.

(f) TESTING

The test pieces were removed from the water on the day when due, cleaned of all moss, sea grass, and shells (if taken from sea water), weighed, and measurements taken. The end surfaces were then covered with a plaster of Paris coating, forming a cap which was made perpendicular to the axis of the cylinder by forming on a glass-top table which was perfectly horizontal and placing a spirit level on the side of the cylinder while "capping." The plaster was made of a mixture of half plaster of Paris and half Portland cement. This set very hard in four or five minutes, when the test piece could be removed from the plate and the other end capped in a similar manner, being made perpendicular to the axis of the cylinder and parallel with the cap first placed.

After capping, the test piece was placed on a spherical bearing block in a compression testing machine and was kept in slight horizontal motion by the operator while the upper head of the



Fig. 19.—*Crate with concrete test pieces before placing in sea water*



Fig. 20.—*Crate with concrete test pieces after storage in sea water*

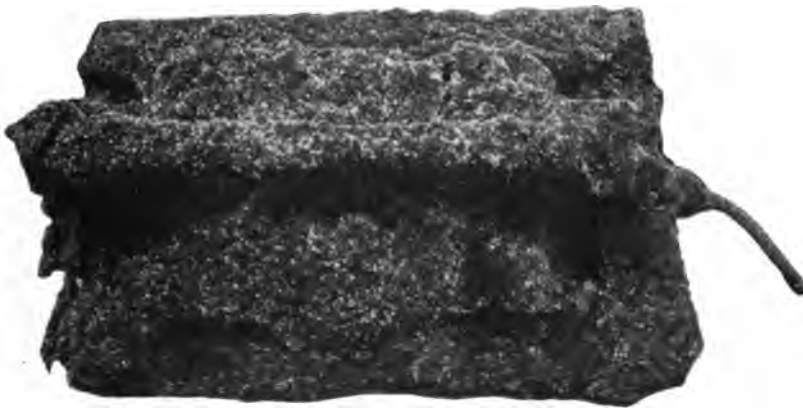


Fig. 21.—*Crate with concrete test pieces after storage in sea water*

machine was brought down onto the test piece. The purpose of this was to keep the head of the machine and the surface of the test piece parallel until the load was "caught," thus making it bear uniformly over the entire surface. The load was constantly applied, the head moving at the rate of 0.02 of an inch per minute, until failure of the test piece or the capacity of the machine was reached.

2. TENSION TEST PIECES

(a) PROPORTIONING

The ratios of the constituent materials of the mortars were assumed according to weight measure.

(b) CONSISTENCY

The normal consistency was predetermined with a Vicat needle for the neat cements, and for Portland cement sand mortars the water equivalent as recommended by the committee on uniform tests of the American Society of Civil Engineers was used. The water required for sand mortars made with natural, slag, or other special cements was judged by eye and the same percentage was used throughout for mixing batches of the same mortar.

(c) MIXING

Ten briquettes were molded from one batch of material. If a mortar, the sand was first weighed and spread out onto the plate-glass-top mixing table, and the cement was weighed and spread evenly on top, after which the operator, wearing rubber gloves, mixed the materials thoroughly, turning them with a trowel and with his hands.

After this dry mixing the materials were spread out to about a 2 or 3 inch depth, a crater formed in the middle, the water poured into the crater, and the dry material on the outer edge was turned into the crater with a trowel. After the water was absorbed the materials were kneaded for about two minutes.

(d) MOLDING

The briquettes were molded in standard three or five gang tension briquette molds. The material was pressed into place by the thumbs of the operator, the mold being turned and both surfaces compacted and troweled.

(e) STORAGE

All test pieces were placed in a moist closet for the first 24 hours after molding, after which the molds were removed. Upon removing the molds all neat cement briquettes were marked with the test number and "gang" number, so that briquettes from the same gang could be identified. Ten gangs, or 50 briquettes (in some cases only 30 briquettes), were made of each cement or mixture. Half of this number were placed in fresh-water storage tanks and the remainder in retaining crates (see Fig. 22) in the sea, but the briquettes of each gang were assorted so that not more than three nor less than two of every gang were placed in sea water. They remained in the water until due to be tested.

(f) TESTING

The briquettes were tested at five different periods—4, 13, 26 weeks, 1 and 2 years—and in most cases five briquettes which had been stored in sea water and five which had been stored in fresh water were tested at each period for each cement. The test pieces were removed from the retaining crates or the fresh-water tanks on the day when due and tested directly after taking from the water before drying. Some of the briquettes a year or more old were not tested for several days after removing from the water, as it was necessary to ship them for testing, but these were packed in wet straw or sea grass, so they did not dry.

3. SOUNDNESS TEST PIECES

The soundness test pieces were in the shape of the standard constancy of volume pat, 3 inches in diameter, one-half inch in thickness at the center, and tapering to a thin edge. The test pieces or pats were molded on 4-inch square glass plates. Two pats were molded from each batch of neat cement, from the same material, and at the same time as the briquettes were molded. They were stored in a moist closet for the first 24 hours, as were the briquettes, after which one was placed in a tank of sea water and the other in a tank of fresh water. The sea water was renewed every other day. The test pieces were observed from time to time and their condition recorded.



Fig. 22.—Crate in which briquettes were stored in sea water



Fig. 25.—Portions of concrete specimens after one year's exposure to sea water, showing cracked surface and layer flaking off

X. RESULTS OF TESTS

1. CONCRETE COMPRESSION TESTS

The compressive strength of 1:2:4 proportion (by volume) Portland cement concretes after exposure for various periods to the chemical action of sea water are given in Tables 11 and 12, p. 118, together with complete notes as to the period of exposure, appearance of concrete, etc., and the results up to the one-year period are illustrated diagrammatically in Fig. 24. In interpreting these results the time of year of making specimens, the weather conditions during the period of exposure, especially during the first few weeks after molding, and all other uncontrollable variables, should be taken into consideration. Referring to the figure, it will be seen that

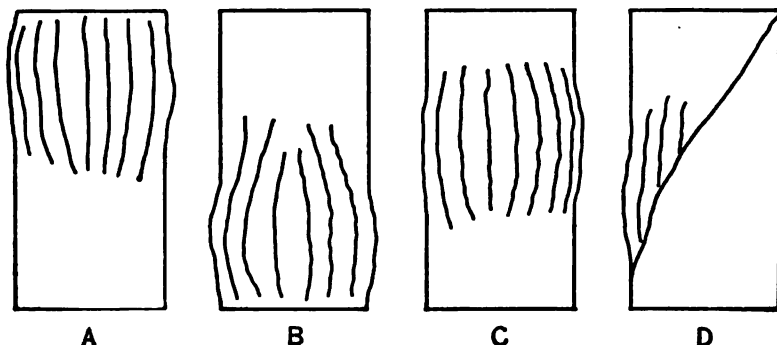


Fig. 23.—Character of failure of concrete test pieces as referred to in tables

the concrete placed through a tremie in sea water develops at 4 weeks only about 33 per cent of the strength of concrete similarly placed through a tremie in fresh water, less than 33 per cent of the strength of similar concrete placed in dry molds and immersed immediately in sea water, and less than 25 per cent of the strength of similar concrete placed in dry molds and immersed immediately in fresh water. Although the concrete placed through a tremie in sea water has a low compressive strength, it shows a constant increase in strength up to one year and practically a constant strength up to $3\frac{1}{2}$ years' exposure. The test piece and tremie necessarily had to be small in dimensions, so as to afford opportunity for testing, but undoubtedly a large tremie used in large forms would give a better quality of concrete, in that

there would be less opportunity for the sea water to penetrate the mass. It is essential that a wet mixture be used to fill all voids of the concrete with water before depositing, so as to prevent the agitation caused by the sea water forcing the air from a dry mixture.

Several other methods of placing concrete were tried. Dumping from a bucket and permitting it to settle through the water, the concrete settled in layers of stone, sand, and cement. In sea

Concrete: 1 Part Portland Cement, 2 Parts Jersey Sand, 4 Parts Trap Rock

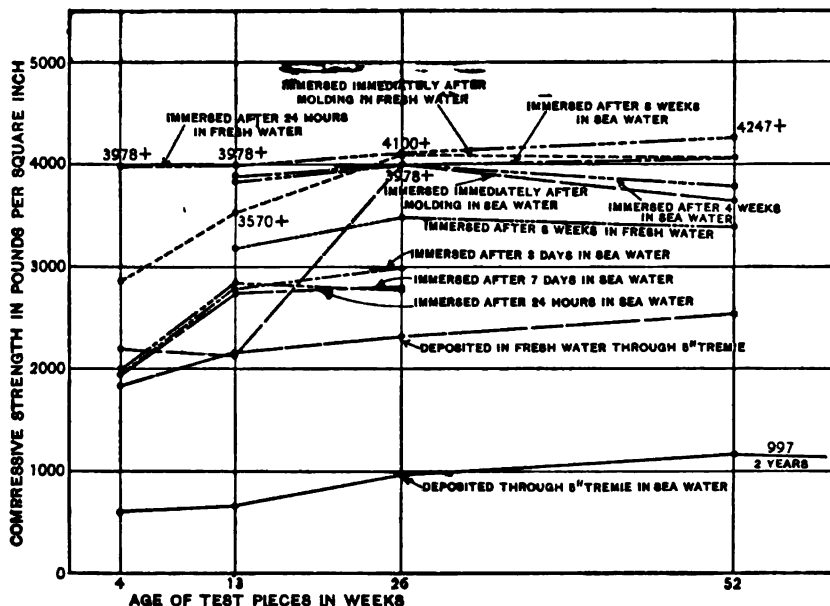


Fig. 24.—Compressive strength of 1:2:4 Portland cement concrete after storage in sea water and fresh water

water so much magnesia was precipitated and deposited between the particles that the mass had very little or no strength excepting in spots. Magnesia would be deposited between the particles and the aggregate would be separated in a similar way if deposited by means of a trough extending to the bottom of the form. It was not possible to deposit concrete from a bottom dump bucket on such a small scale as to make it at all comparable with practice. But referring to Fig. 24, it will be seen that concrete sets and hardens

practically as well under sea water as under fresh water or in the atmosphere; thus the problem seems to be one of getting the concrete in place without the separation of the aggregate and with as little exposure of the cement as possible, which causes the magnesia of the sea water to be precipitated and deposited in the mass of the concrete.

With a few exceptions it will be observed that all of the concrete, both that exposed in sea water and that exposed in fresh water, shows a slight decrease in strength from 26 to 52 weeks. It is not possible to state whether this is peculiar to the cement used or whether the freezing winter weather affected the fresh-water specimens and that the chemical action of the sea water is responsible for the decrease in strength of the sea-water specimens. The fresh-water test pieces were immersed in a large iron tank and during the winter, although the tank was covered, there were periods during which the water was frozen solid. In the case of the concrete test pieces aged for one, three, and seven days before immersion in sea water, it will be observed that they were made during October, November, and December, when the temperature was comparatively low, so that they would naturally harden more slowly than those made during the spring or summer months. The temperatures of fresh water and sea water are given in Fig. 60.

In Fig. 25 is shown a section of two concrete cylinders which were exposed between tides from December 23, 1909, until the following spring. It will be noted how the surface is cracked and flaking off.

In order to distinguish between frost action and chemical action, another series of exposure tests have been started, part of the test pieces to be exposed off the northern coast and a part to be exposed off the southern coast.

The 200 000-pound capacity testing machine was found to be too small for testing many of the 1 : 2 : 4 proportion concrete specimens and therefore another series of tests was made of concrete in the proportion of 1 part Portland cement to 3 parts of sand and 6 parts of stone or gravel (by volume). The results of these tests are given in detail in Tables 13 and 14 and the results of the compressive strength tests are shown diagrammatically in Fig. 26. The compressive strength of the concrete placed through a tremie

in sea water is slightly less than that placed through a tremie in fresh water, although there is not a great difference. The concrete which was permitted to set or harden for eight weeks before immersion in sea water has more than three times the strength of the concrete placed through a tremie. All of the concrete seems to have a greater strength in sea water than in fresh water after four weeks' immersion, but at later periods the concrete immersed

Concrete: 1 Part Portland Cement, 3 Parts Jersey Sand, 6 Parts Trap Rock or Gravel

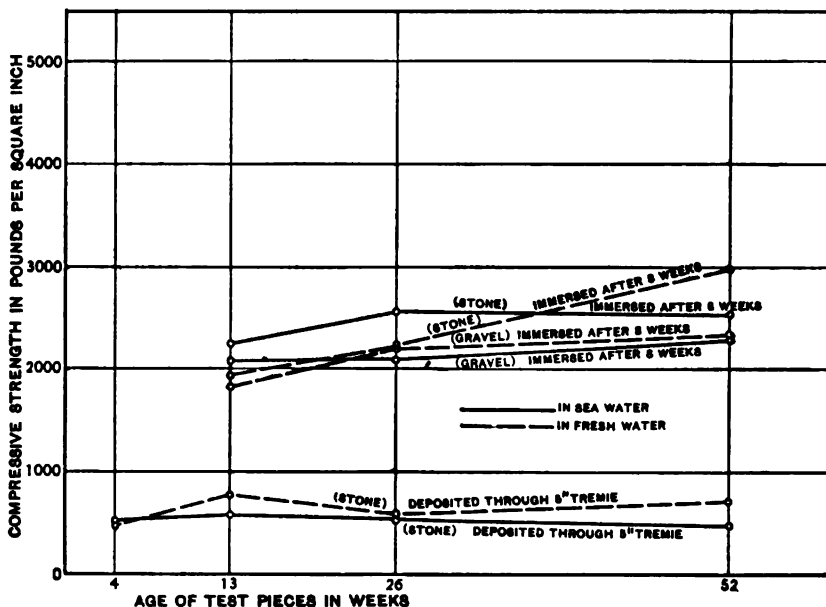


Fig. 26.—Compressive strength of 1:3:6 Portland cement concrete after storage in sea water and fresh water

in fresh water is the stronger with one exception. This higher strength after short periods of immersion is also characteristic of the neat tensile briquet tests, but to a greater extent, as shown in Figs. 37 to 59. The results of the $2\frac{1}{2}$ -year tests are most significant in showing an increase in strength over previous periods and no deleterious effects from sea water exposure.

In Tables 15 and 16 (p. 125) and Fig. 27 are given the results of tests of a very lean concrete made in the proportion of 1 part

Portland cement to 4 parts of sand to 8 parts of stone. This concrete was so lean it was not possible to place it through a tremie so that it would become hard enough to handle and remove the molds. It will also be observed in these tests that the sea-water test pieces have a greater strength for short periods than those immersed in fresh water.

The results of tests of concretes made with different kinds of cement are given in Tables 17 and 18 (p. 127) and Fig. 28. It is

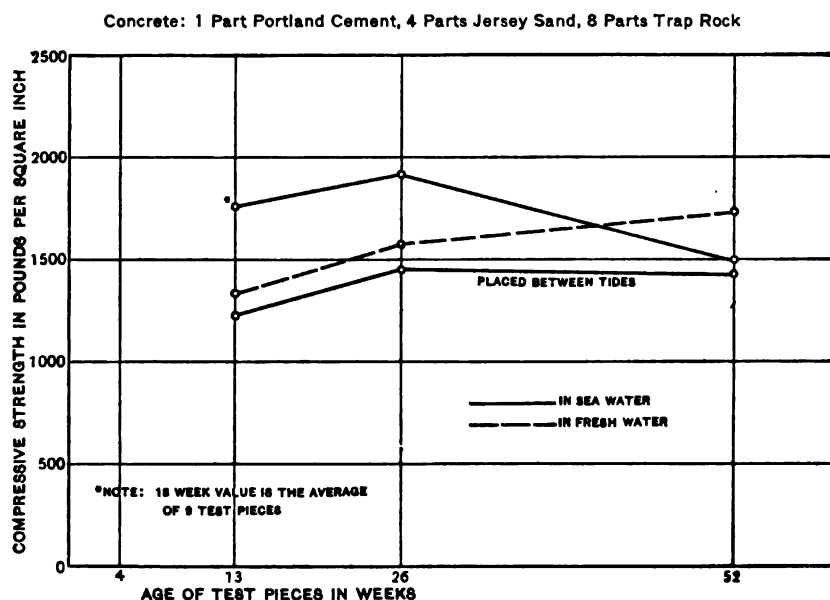


Fig. 27.—Compressive strength of 1:4:8 Portland cement concrete after storage in sea water and fresh water. Test pieces stored for 8 weeks in damp room previous to immersion

interesting to observe that the concrete made with cement No. 4 has a higher compressive strength at the end of a year than the concrete made with typical Portland cement No. 47. In both of these series the test pieces were made about the same time of the year, although a year apart, so that they were subjected to approximately similar weather conditions. This higher strength value need not be attributed however to the iron content as undoubtedly the same results could be obtained with normal Portland cement.

The strength of 1:2:4 proportion concrete using seashore sand, which is very fine grained and uniform in size, in place of the well-graded Jersey sand, is greater than had been expected and interesting in connection with the statements of A. Bauchere¹⁷ that even fine-grained sands do not make durable sea-water mortars. The results are given in Tables 19 and 20 (p. 137) and Fig. 28. The concrete made with seashore sand developed about 33 per cent less strength than concrete made with Jersey sand at 4 weeks and 20

Concrete: 1 Part Cement, 2 Parts Sand, 4 Parts Trap Rock

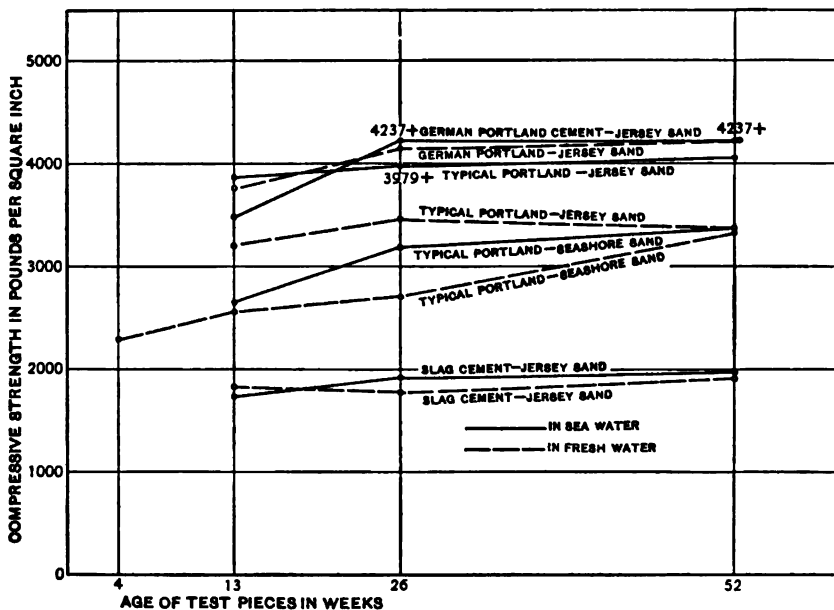


Fig. 28.—Compressive strength of 1:2:4 concrete made with various cements after storage in fresh water and sea water

per cent less at 52 weeks for that stored in sea water, and about 30 per cent less at 4 weeks and equal strength at 52 weeks for that stored in fresh water. The possibility of temperature and freezing effects should also be taken into consideration in making this comparison.

In Table 21 (p. 139) and Fig. 29 are given the results of a series of compression tests of concrete cylinders made of pit run Gorgona gravel No. 55. Part of the test pieces were stored in damp room,

¹⁷ Manager of the Societe des Cements Francais; Engineering (London), 88, p. 655.

part in tanks of fresh water, and part in tanks of sea water, tests being made at periods ranging from eight weeks to one year. None of these test pieces were exposed to freezing temperatures, and it will be observed that the concrete exposed to sea water hardened slower than the others, but at the end of one year its strength is slightly greater than either of the others. The initial modulus of elasticity and the yield point were also determined upon these test pieces, the concrete immersed in sea water giving

Concrete: 1 Part Portland Cement, 6 Parts Pit Run Gravel No. 55

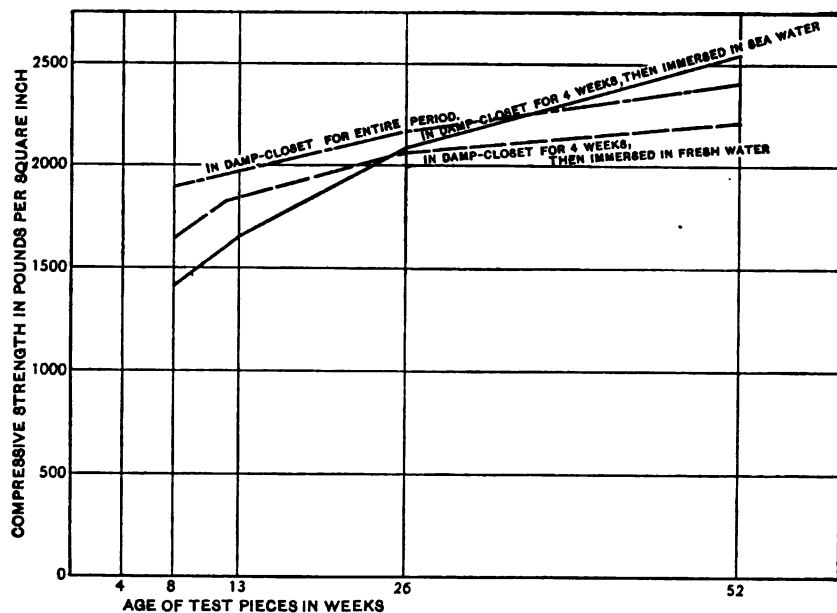


Fig. 29.—Comparison of compressive strength of Portland cement concrete after storage in fresh water, sea water, and damp atmosphere

as high or higher results than that immersed in fresh water or stored in the damp room.

In connection with the proposed use of certain types of reinforced concrete piles in the construction of docks at the Canal Zone several series of tests were made with aggregates from the Isthmus having metal of various forms embedded. The test pieces were made as shown in Fig. 30. They were broken open and the embedded metal examined at periods ranging from eight

weeks to two years. The results of these tests are given in Tables 22 and 23 (p. 142).

The concrete for the test pieces reported in Table 22 was made in the proportion of 1 part Portland cement to 1 part sand to 5 parts gravel, which was found by test to be the mixture which gave the maximum density for these materials where the ratio of cement to aggregate was 1 to 6. Practically all of the metal

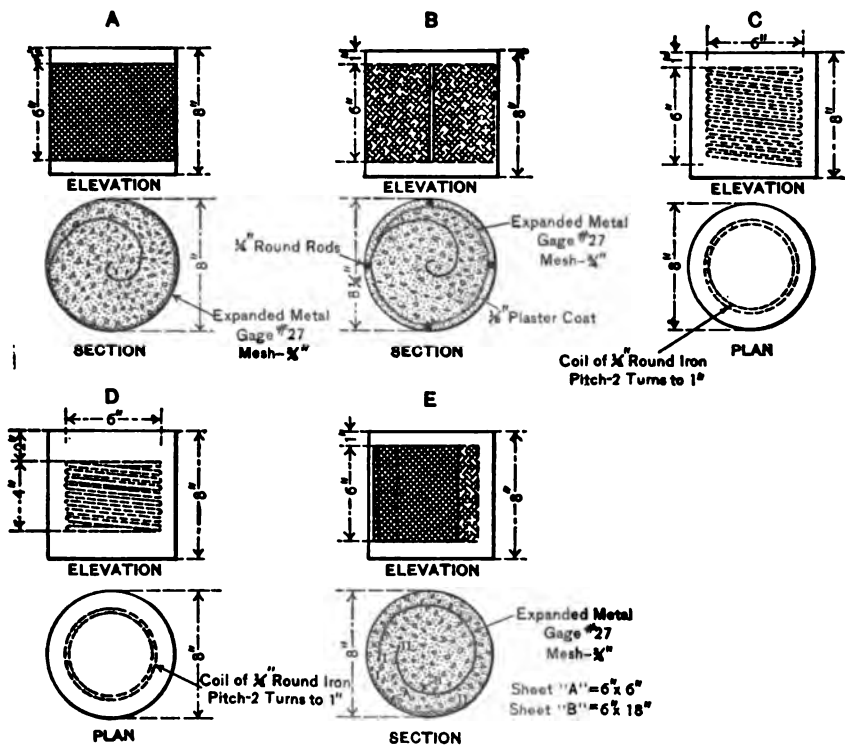


Fig. 30.—Diagram of metal corrosion test pieces

embedded within an inch of the cylindrical surface is more or less corroded. Where the metal was placed as shown in Fig. 30a, it is corroded somewhat to the depth of about an inch from the cylindrical surface, and in some cases the entire metal is corroded. In the case of the spiral reinforcement, which was embedded within about an inch of the cylindrical surface, it was practically all more or less corroded. While the 1:1:5 proportion gave the



Fig. 31.—Pats of neat cement with various percentages of plaster of Paris added. Stored in sea water 22 months

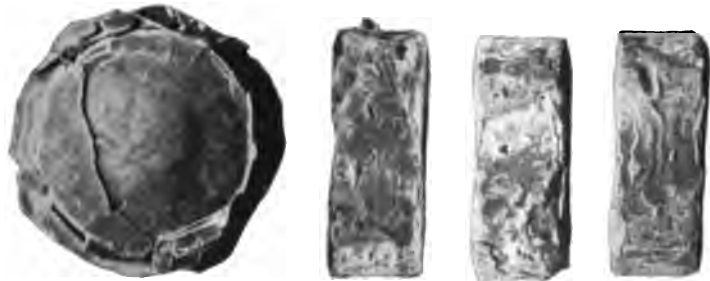


Fig. 32.—Neat cement pat and briquettes made of cement No. 5 with 50 per cent of lime added. Stored in sea water for two months

maximum density for these materials, undoubtedly a mixture containing a greater percentage of fine material would have been more efficient in coating and protecting the metal.

All of the metal embedded 2 inches or more from the surface is practically clean, and there seems to be no difference in the condition of the metal whether the concrete was immersed or placed between tides.

From the results given in Table 23 (p. 144) it will be observed that, although the metal in the interior did not extend to the outer surface, the metal within an inch of the surface was in most cases somewhat corroded, while that 2 inches or farther from the surface was practically clean.

2. SOUNDNESS TESTS

In Table 24 (p. 147) are given the comparative results of soundness tests in which neat pats of various cements were immersed in fresh water and in sea water. These results cover a period slightly less than two years and show the characteristics of the failure of cements when exposed to sea water in this form. Practically all of the cements were sound in fresh water, while in sea water practically all showed evidence of physical change and unsoundness, even the natural and the slag cements. It is interesting to note that in most cases the greatest evidence of unsoundness occurs during the first 12 months, after which there is little change in the appearance of the pats. The pat made of cement No. 4, which was of high iron composition, showed less evidence of warping and cracking than any of the other Portland cements, although the entire surface loosened up from the body of the pat. Excrecence was used to designate the salts which appear on the surface of the pat due either to deposit from the sea water or issuance from the cement, as shown in Figs. 31 and 33. By a "convex warp" is meant the rounding up of the edges of the pat while the center remained on the glass, and a "concave warp" the raising of the center while the edges remained on the glass. The excrecence was found to be practically a magnesia hydrate. Following are analyses of samples of coating as found on the pats and briquettes soon after they were placed in sea water.

	Sample No. 1	Sample No. 2
SiO ₂	1.58	2.06
Al ₂ O ₃.....	.64	.43
Fe ₂ O ₃		
CaO.....	8.26	10.66
MgO.....	35.36	52.08
SO ₃	1.08	.66
Cl.....	4.55	(*)
CO ₂	3.04	6.49
Remainder, H ₂ O mostly.....	45.49	27.62
	100.00	100.00

* Sample too small for determination.

The deposition of a white coating or improperly so-called "laitance" has been observed by E. Maynard ¹⁸ and many other investigators.

The effect of increasing the sulphate content of a cement by adding plaster of Paris in a small pebble mill was tried with four typical cements—Nos. 4, 5, 24, and 52, a high iron Portland, a normal Portland, a slag, and natural cement, respectively. Both tension briquette tests and soundness tests were made. The soundness tests on cement No. 4 are given in Table 25. It is very interesting to note that an addition of plaster of Paris up to 20 per cent by weight of the cement did not have a marked effect upon its soundness in sea water. This is in contrast to the effect of adding plaster to cement No. 5, Table 26, and also Figs. 37 to 54, giving results of briquette tests. The salts found issuing from under the pat in fresh water were analyzed as calcium carbonate.

In Table 26 (p. 152) are given the results of soundness tests of cement pats made of cement No. 5, with the addition of various percentages of plaster of Paris. The fresh-water pats remained sound with an addition up to 2 per cent of plaster of Paris, after which they were warped slightly until with 20 per cent of plaster added they were badly warped and cracked. In Fig. 31 are shown some of the sea-water pats after about one year's immersion. With an addition of plaster up to 1.5 per cent the edges curve up; above 1.5 per cent the center is raised and the edges remain on the glass. These tests were repeated several times with similar results. In

¹⁸Cement Age, 5, No. 3, p. 191.



Fig. 33.—Neat cement pat made of cement No. 5 with 2 per cent of plaster of Paris added. Stored in sea water for one year



Fig. 34.—Interior of briquettes made of cement No. 5, showing crystals. Stored in sea water for one year

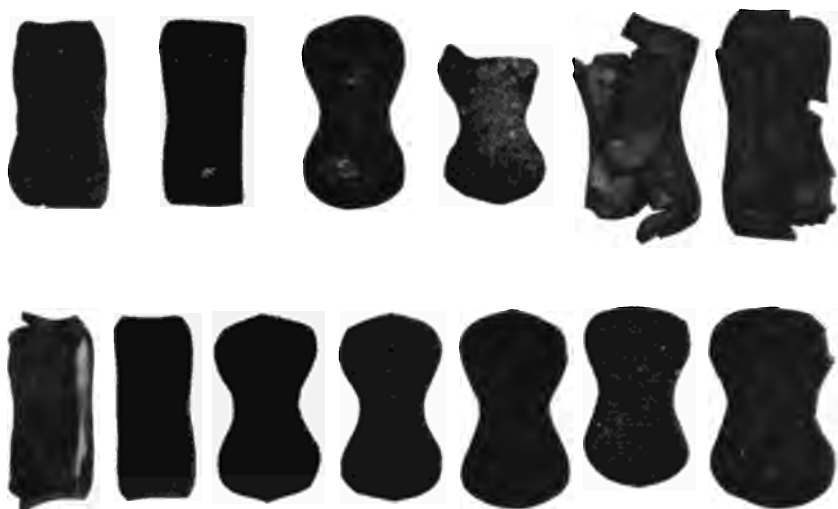


Fig. 35.—*Appearance of briquettes after storage in sea water, showing increase in volume and character of disintegration*

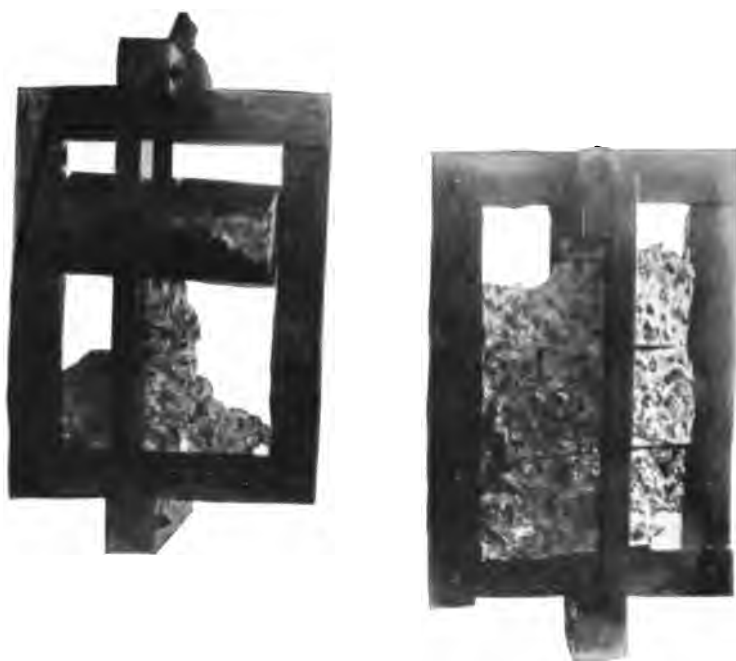


Fig. 36.—*Concrete cylinders after 16 days' immersion in sea water. Fifty per cent of cement was replaced by lime*

Fig. 33 is shown pat made of cement with 2 per cent of plaster. It is interesting to note the local swelling showing evidence of localized expansion. A surface layer one-sixteenth inch thick was raised in places three-sixteenths inch above the remaining surface. Portland cement No. 5 with the sulphate content increased did not remain as sound in sea water as cement No. 4, which contains a lower percentage of aluminum and a higher percentage of iron.

In Table 27 (p. 154) are given the results of a series of soundness tests in which dolomitic lime was added to cement No. 5 in percentages varying from 0.5 to 50 per cent. In fresh water all pats remained sound with the exception of a very slight warping in some cases. In sea water the disintegration is proportional to the addition of lime. The pat with 50 per cent of lime is shown in Fig. 32 after two months' immersion. It is coated heavily with magnesium hydrate, which can better be observed on the briquettes made from a similar mixture. All pats failed by the edges rounding up.

Four sets of concrete cylinders were made, to which dolomitic lime No. 3 and high calcium lime No. 3b were added, by replacing 25 and 50 per cent by weight of the cement with each lime in a 1:2:4 proportion concrete mixture, using cement 47, Jersey sand, and trap rock. The results of tests were as follows: With 50 per cent of lime, after 16 days' immersion in sea water, the cylinders appeared as shown in Fig. 36. With one exception, only a portion of each cylinder remained in the crates. Those made with high calcium hydrate Nos. 241 to 243 were very soft and chalky and entirely disintegrated, so that the concrete could be easily crumbled and pulled apart by the fingers. The cylinder which is still hanging together is very badly cracked and is ready to fall apart. Only a very little white deposit (MgO) could be observed, and that was near the surface.

In the cylinders made with dolomitic lime the white deposit (MgO) could be observed to the center of the mass, but the pieces of concrete remaining in the crate were much harder than the high calcium lime specimens and could not be crumbled in the fingers.

The results of compression tests of concrete in which 25 per cent of the cement was replaced by lime are as follows: All test

pieces were made November 22, 1909, immersed in sea water December 20, 1909, when 4 weeks old, and tested November 22, 1910, at the age of 1 year.

High calcium lime	Compressive strength (pounds per sq. in.)	Character of failure	Weight per cubic foot
244	1383	C	148.8
245	1723	A	153.1
246	2334	D	153.5
	1813	.....	151.8

These were examined from time to time and two months after immersion the surface of 244 was found to be flaking off to a depth of one-fourth to one-half an inch and the cylinder was covered with deep cracks. Cylinder 245 was also covered with deep cracks in which appeared a white deposit, while 246 showed only a few hair cracks on the surface. All three cylinders were found to be completely saturated with water when tested and a white deposit was observed to a depth of one-half inch from the cylindrical surfaces and $1\frac{1}{2}$ inches from the end surfaces.

Dolomitic lime	Compressive strength (pounds per sq. in.)	Character of failure	Weight per cubic foot
238	2180	C	153.2
239	2080	B	150.9
240	2324	C	150.9
	2195		151.7

No cracks were observable on the surface. All cylinders were completely saturated and a white deposit was observed to a depth of one-half inch from the cylindrical surfaces and $1\frac{1}{2}$ inches from the end surfaces.

3. TENSION TESTS

The results of briquette tests including the one-year tests are shown diagrammatically in Figs. 37 to 59. The results of the two-year tests are given in Table 28 (p. 156). Each individual value is given on the diagrams and a curve is drawn through the average

values so that the fresh-water and sea-water results can be readily compared. The individual results are so arranged that for the sea-water and fresh-water briquettes which were originally made in the same mold the results are placed one above the other. For example, in Fig. 37, cement 4, the sea-water briquette breaking at 685 pounds was originally made in the same mold as the fresh-water briquette breaking at 530 pounds, although they were stored in sea and fresh water, respectively, which eliminates to a large extent the effect of the personal equation in molding. The results of tests on Portland cements are shown in Figs. 37 to 42. It seems to be characteristic of nearly all of the Portland cements to obtain a high early strength in sea water and then decrease in strength very rapidly. The three marked exceptions are cements 41, 48b, and 53, which can not be readily explained. In almost every case the fresh-water results show retrogression at the end of a year. The three exceptions are cements 4, 47, and 53.

The cements containing a high percentage of iron, flux more readily than the high alumina or normal Portland cements and form a much harder and denser clinker at lower temperatures. Cement No. 53 is a Portland of approximately normal composition excepting low SO_3 , but it has every appearance of being made from a very hard burned clinker. While it hardened slowly, it showed a progressive increase in strength with age both in sea water and fresh water.

Spencer B. Newberry¹⁹ and many other investigators have found that the high iron cements when exposed to sea water in the neat form resist decomposition much better than most normal Portland cements. However, the results of tests reported in Part I of this paper show that the high iron cements when brought into intimate contact with sea water and other solutions react just as rapidly as the cements of normal Portland composition.

A chemical analysis of one briquette each from sea water and fresh water of cement No. 5 after 26 weeks' immersion gave the following results (calculated on a water-free basis).

¹⁹ *Mun. Engineering*, 84, No. 4, p. 223.

	Sea water	Fresh water
Tensile strength (pounds).....	50	850
SiO ₂	20.10	20.73
Al ₂ O ₃	10.11	10.30
Fe ₂ O ₃		
CaO.....	62.09	63.61
MgO.....	2.63	2.35
SO ₃	1.65	1.60
Cl.....	2.02	.....
Na ₂ O.....	.31	.....
K ₂ O.....	.54	.....
CO ₂.....	.53	.46

Similar analysis of one briquette each from cement 23 after immersion for 26 weeks in fresh water and sea water gave the following results (calculated on a water-free basis):

	Sea water	Fresh water
Tensile strength (pounds).....	80	700
SiO ₂	20.02	20.82
Al ₂ O ₃ and Fe ₂ O ₃	10.70	11.14
CaO.....	62.06	63.37
MgO.....	2.88	2.84
SO ₃.....	.36	.35
Na ₂ O.....	.47	.....
K ₂ O.....	.49	.....
CO ₂.....	.53	.51
Cl.....	2.50	.....

The SO₃ was determined upon a sample from the outer one-eighth inch and a sample from a one-half cube cut from the center of a briquette of cement Nos. 4 and 5 after six months' exposure to sea water, with the following results:

	Exterior	Interior
Cement 4 (per cent of SO ₃ found).....	2.25	1.81
Cement 5 (per cent of SO ₃ found).....	2.29	1.56

Thus, both of these cements show they absorbed approximately the same percentage of SO₃. A similar determination was made of a briquette made of cement No. 5, to which 20 per cent of lime No. 3 had been added, which had been exposed to sea water for one year. The outer crust, about one sixty-fourth inch thick,

was flaked off and analyzed, as well as the outer one-eighth inch undercrust, and a one-half inch cube cut from center: SO_3 in crust, 1.34 per cent; in exterior undercrust, 4.81 per cent; and in interior, 1.52 per cent.

The appearance of the interior of a broken briquette made of cement No. 5 after one year's exposure to sea water is shown in Fig. 33. Fig. 35 illustrates the appearance and manner of disintegration of some briquettes which were stored in sea water. Some of them showed as much as one-half inch increase in length.

In the following table are the results of the analyses of five briquettes made of cement No. 5 with various percentages of lime No. 3 added.

Analysis of Neat Cement Briquettes After 12 Weeks' Immersion in Sea Water (calculated on a water-free basis)

	Cement No. 5 (tensile strength 45 pounds)			Cement No. 5+ $\frac{1}{2}$ per cent lime No. 3 (tensile strength 840 pounds)			Cement No. 5+2 $\frac{1}{2}$ per cent lime No. 3 (tensile strength 730 pounds)		
	A	B	C	A	B	C	A	B	C
SiO_2	10.51	20.01	20.09	10.44	20.16	20.31	8.77	19.79	20.29
Al_2O_3	3.90	7.05	7.88	4.29	7.61	7.51	3.53	7.73	7.50
Fe_2O_3	1.62	2.38	2.47	1.60	2.31	2.44	1.19	2.31	2.47
Cl.....	2.05	2.53	1.47	1.96	2.51	1.30	1.71	2.52	1.33
CaO.....	47.90	60.29	60.90	48.13	59.89	61.23	46.79	59.68	60.50
MgO.....	13.20	3.36	3.19	12.66	3.13	3.31	14.12	3.58	4.01
SO_3	2.16	1.85	1.55	1.92	1.83	1.55	1.81	1.87	1.59
Na_2O}.....	.69	.53	.61	.52	.50	.43	.66	.60	.53
K_2O}.....	.30	.49	.53	.21	.47	.35	.30	.46	.39
CO_2	18.15	2.08	1.64	18.71	2.15	1.87	21.50	2.03	1.67

	Cement No. 5+4 per cent lime No. 3 (tensile strength 700 pounds)			Cement No. 5+5 per cent lime No. 3 (tensile strength 125 pounds)		
	A	B	C	A	B	C
SiO_2	6.38	19.60	19.89	7.51	19.95	19.59
Al_2O_3	2.19	7.30	7.52	2.47	7.59	7.47
Fe_2O_3	1.12	2.31	2.53	1.17	2.26	2.54
Cl.....	1.63	2.54	1.51	1.40	2.40	1.40
CaO.....	44.01	59.99	59.79	46.21	59.73	60.27
MgO.....	18.34	4.11	4.19	16.27	4.13	4.35
SO_3	1.55	2.01	1.53	1.56	1.66	1.53
Na_2O}.....	.89	.41	.59	.27	.42	.54
K_2O}.....	.33	.34	.49	.17	.40	.41
CO_2	23.94	1.95	2.31	23.28	2.02	2.18

NOTE.—A=surface crust; B= $\frac{1}{8}$ -inch layer just under crust; C=interior of head of briquette.

The increase of SO_3 and MgO content near the surface of concrete after exposure to sea water was observed by the committee of German Portland-cement manufacturers,²⁰ Prof. Brazier, Philip J. Messent,²¹ Harrison Hayter,²² and others.

An interesting series of results is shown in Fig. 40, cement 47, in which the briquettes were immersed in fresh water for several days before immersion in sea water. Those permitted to harden in fresh water for three days before immersion in sea water show very much less retrogression in strength with age. These results are in accord with the observations of Vicat, E. Mayer,²³ L. Deval,²⁴ and many others. The results of test of cement 53 illustrated in Fig. 41 are interesting in that neither the fresh nor sea water results show any retrogression up to the year period. At two years the fresh-water results show slight retrogression, but sea-water results show no retrogression. This is a very coarsely-ground cement made from a very hard burned clinker of approximately normal chemical composition for a Portland cement excepting for the low SO_3 content. Cement 34, Fig. 38, and cement 41, Fig. 39, which are also of normal Portland composition, had abnormally high tensile strength in sea water at all periods including two years. The results of test of cement 55 are interesting, showing a big decrease in strength at 13 weeks and a later increase to one year. At two years, however, it had very little strength in sea water.

In Figs. 42 to 44 are given the results of tests of neat natural and slag cements. The slag cement 24b shows the same inclination as the Portland cements to retrogress in strength with age in sea water. The natural cements 26b, 27, 28, 32, 33, and 52, Figs. 43 and 44, differ only slightly in fresh water and in sea water up to the one-year period. At two years they all show less strength in sea water than in fresh water. Cement 57, Fig. 44, which is an improved slag cement, acts similarly to 24b, showing a considerable retrogression in strength with age in sea water, having very little strength at the end of two years in sea water. Cement 57b, which is of the same brand and similar composition as cement 57, showed little retrogression in tensile strength, either in fresh water

²⁰ *Cement Age*, 5, No. 4, p. 262.

²¹ *Proceedings Institute of Civil Engineers*, 107, p. 73.

²² *Proceedings Institute of Civil Engineers*, 87, p. 162.

²³ *Engineering (London)*, 82, p. 655.

²⁴ *Cement*, 2, p. 110.

or sea water up to the two-year period, and its strength is practically equal to a Portland cement.

The results of briquette tests of cement mortars immersed in sea water and fresh water are given in Figs. 45 and 46. In the mortar briquettes there is much less evidence of sea-water action than in the neat briquettes. In several cases the normal Portland cements showed practically equal strength up to the two-year period in both fresh and sea water, in the form of mortar briquettes, but had no strength in sea water at 26 weeks in the form of neat briquettes.

It will be observed that the sea-water mortar briquettes show a low strength at four weeks, but in every case an increase in strength at the end of a year, which is in marked contrast to the results of the neat cement briquettes. With one or two exceptions the 2-year results show little change from the one-year results. These results are substantially the same as those obtained by M. Gary²⁵ on 1:2, 1:3, and 1:4 mortars over a period of six months. 1:2, 1:3, and 1:4 mortars over a period of six months.

In Figs. 47 to 49 are given the results of tests in which plaster of Paris was added to cement No. 4 in various percentages. With the addition of 0.5 per cent of plaster the strength in fresh water was materially increased and showed no retrogression up to two years. The sea-water briquettes are practically unaffected. As the percentage of plaster increases the strength decreases slightly in both fresh and sea water, until with 3 and 3½ per cent of plaster the sea-water briquettes show marked retrogression from four weeks to one year. With from 4 to 20 per cent of plaster the strength is somewhat reduced at the early periods, but an increase in strength is shown from four weeks to one year in both fresh water and in sea water. At two years the strength is reduced in sea water.

The results of tests in which plaster of Paris was added to slag cement No. 24b are given in Figs. 49 to 51. With the increase in the percentage of plaster added there is a decrease in strength in both fresh-water and sea-water briquettes up to the one-year period until with 5 per cent of plaster the sea-water briquettes have practically no strength and with 10 per cent of plaster the fresh-water briquettes have practically no strength.

The results of a series of tests in which plaster of Paris was added to typical Portland cement No. 47 are given in Figs. 51 to 53.

²⁵ Proceedings Institute of Civil Engineers, 107, p. 73.

With an increase in the percentage of plaster added there was a decided increase in strength of the sea-water briquettes until with 3.0 per cent of plaster the sea-water briquettes show a marked increase in strength from four weeks to one year, the strength being greater in sea water than in fresh water. At the end of two years the sea-water briquettes have less strength than at four weeks excepting with addition of 5 per cent of plaster. With the addition of 3.5 per cent of plaster the fresh-water and sea-water briquettes have about the same strength and with further increase of plaster both the fresh-water and the sea-water briquettes show a decrease in strength, the sea-water curve falling below the fresh-water curve until with 10 per cent of plaster the sea-water briquettes have no strength at the end of a year. With the addition of 15 per cent of plaster the sea-water briquettes show an increase in strength from four weeks to one year, although the curve lies below the fresh-water curve. These results are similar in a general way to those obtained by Clifford Richardson,²⁶ but contrary to those obtained by H. Le Chatelier.²⁷

These tests were duplicated, using another Portland cement, with substantially the same results.

A rather striking result of the addition of the plaster is shown in the uniformly increasing strength with age in all but a few cases with the briquettes stored in fresh water.

The results of adding plaster of Paris to a natural cement No. 52 are given in Fig. 54. Both the fresh-water and sea-water briquettes show a decrease in strength with the increase in the quantity of plaster added until with 2 per cent the sea-water briquettes have lost all strength and the fresh-water briquettes have only 33 per cent of the strength at four weeks and 75 per cent of the strength at one year as they had without the addition of plaster.

In Figs. 54 to 59 are given the results of tests of the ammonium carbonate series in which both neat and sand mortar briquettes were made of mixtures to which various percentages of ammonium carbonate was added with the mixing water as a means of forming the carbonates of lime which is rather inert in sea water. With the neat slag cement, the addition of 1 per cent of ammonium carbonate reduces slightly the strength of both the fresh-water and

²⁶ *Engineering Record*, 55, No. 3, p. 86.

²⁷ *Municipal Engineering*, 20, No. 6, p. 147.

sea-water briquettes. With the addition of 5 per cent the strength is slightly reduced in sea water for the 26 and 52 week periods. With 10 per cent of ammonium carbonate added, the sea-water briquettes show a lower than normal strength at 4 weeks, but the results are about normal with the untreated mortar for later periods. The individual results are for the most part very widely scattered. With the slag cement sand mortar the ammonium carbonate seemed to have practically no effect either when added to the mixture or when the briquettes were placed in a solution of ammonium carbonate before immersion in sea water or fresh water. The ammonium carbonate added to the neat typical Portland cement had little effect upon the strength of the briquettes stored in fresh water, but the 1 per cent solution increased the strength of the briquettes stored in sea water, for all periods subsequent to 4 weeks. With 5 per cent of ammonium carbonate, the strength of sea-water briquettes is still greater than with the 1 per cent solution, excepting at the 13-week period, but with 10 per cent of ammonium carbonate the strength is less than with the 1 or 5 per cent solutions, although greater than without any ammonium carbonate. At the end of two years none of the sea-water briquettes had practically any strength.

The addition of the ammonium carbonate to the Portland cement sand mortar slightly reduced the strength with the increase in quantity of ammonium carbonate up to 10 per cent. Where the sand mortar briquettes were placed in a solution of ammonium carbonate before immersion, the fresh-water briquettes gave about the same strength as the untreated, but the sea-water briquettes show a greater strength than the untreated sea-water briquettes and about the same strength as the similarly treated fresh-water briquettes at all periods prior to two years, but less strength at this period.

The addition of ammonium carbonate to the neat natural cement slightly reduced the strength of the sea-water briquettes at the early periods but had little or no effect upon the strength at the later periods. The strength of the fresh-water briquettes is slightly reduced with the increase in ammonium carbonate. The addition of ammonium carbonate up to 10 per cent to the natural cement sand mortars had practically no effect upon the strength.

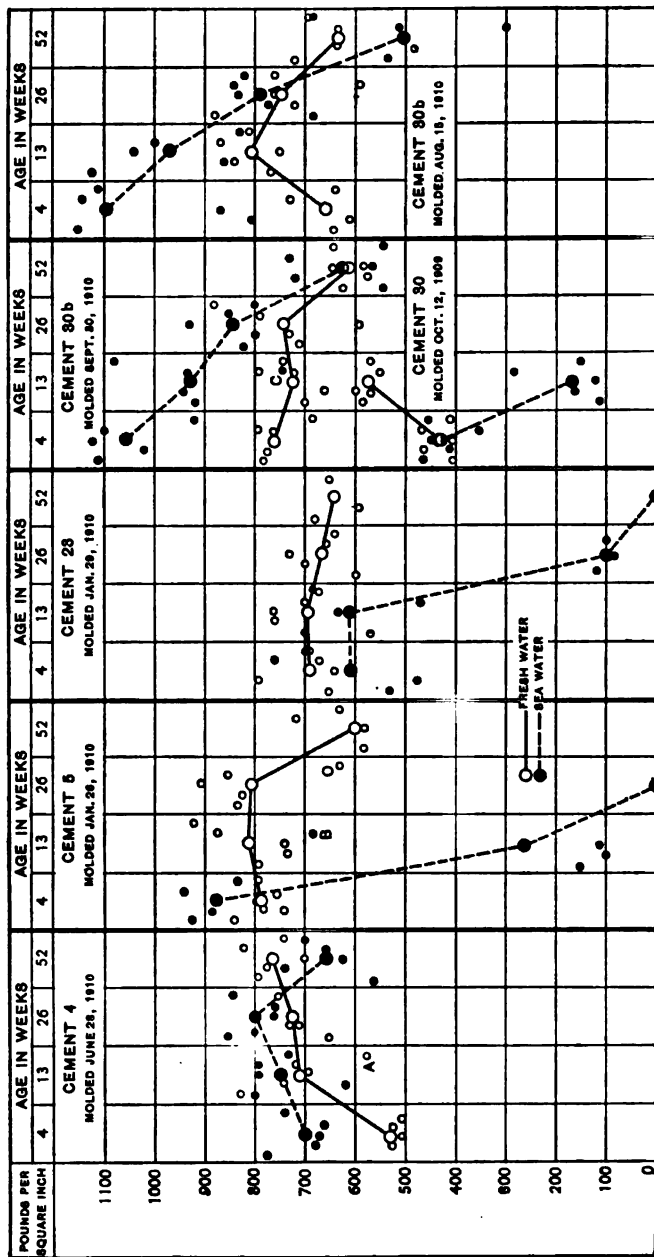


Fig. 37.—Tensile strength of neat Portland cements 4, 5, 23, and 30, stored in damp room 24 hours before immersing. Specimens completely saturated in sea water. Cement 5 at 13 weeks, cement 23 at 13 weeks (excepting specimen marked B), cement 30 and 30b at 52 weeks. Cement 4, sea-water specimens, were slightly blistered on troweled surface. Cement 5, sea-water specimens, failed at less than 10 pounds at 26 weeks, and were found cracked in crate at 52 weeks. Cement 23, sea-water specimens, hair cracked at 26 weeks, and had no strength at 52 weeks. Cement 30, specimen C, had void in center. Two year tests given in Table 28 (p. 156)

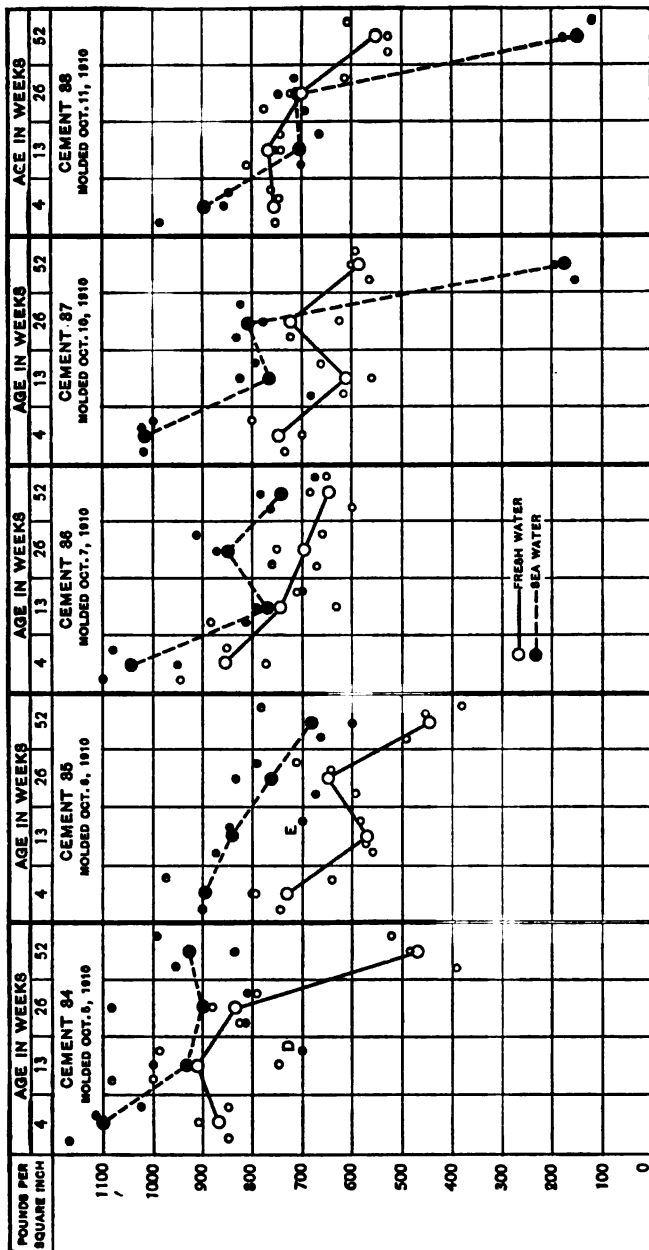


Fig. 38.—Tensile strength of neat Portland cements 34, 35, 36, 37, and 38, stored in damp room 24 hours before immersing. Specimens completely saturated in sea water. Cement 34, specimen D, and all 52-week specimens; cement 35 at 26 and 52 weeks; cements 36, 37, and 38 at 52 weeks. Cement 35, specimen E, failure due to machine

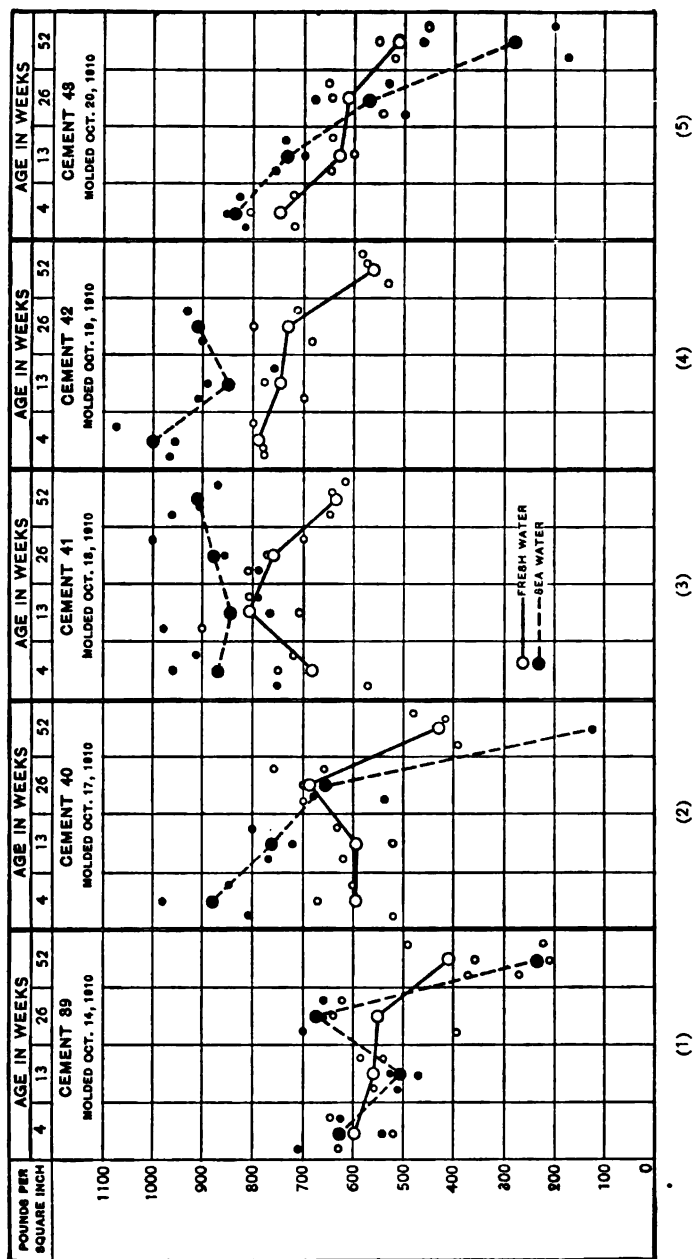


Fig. 39.—Tensile strength of neat Portland cements 39, 40, 41, 42, and 43, stored in damp room 24 hours before immersing. Specimens completely saturated in sea water. Cement 39 at 13, 26, and 52 weeks; cement 40 at 26 and 52 weeks; cement 41 at 26 and 52 weeks; cement 42 at 26 weeks; cement 43 at 26 and 52 weeks.

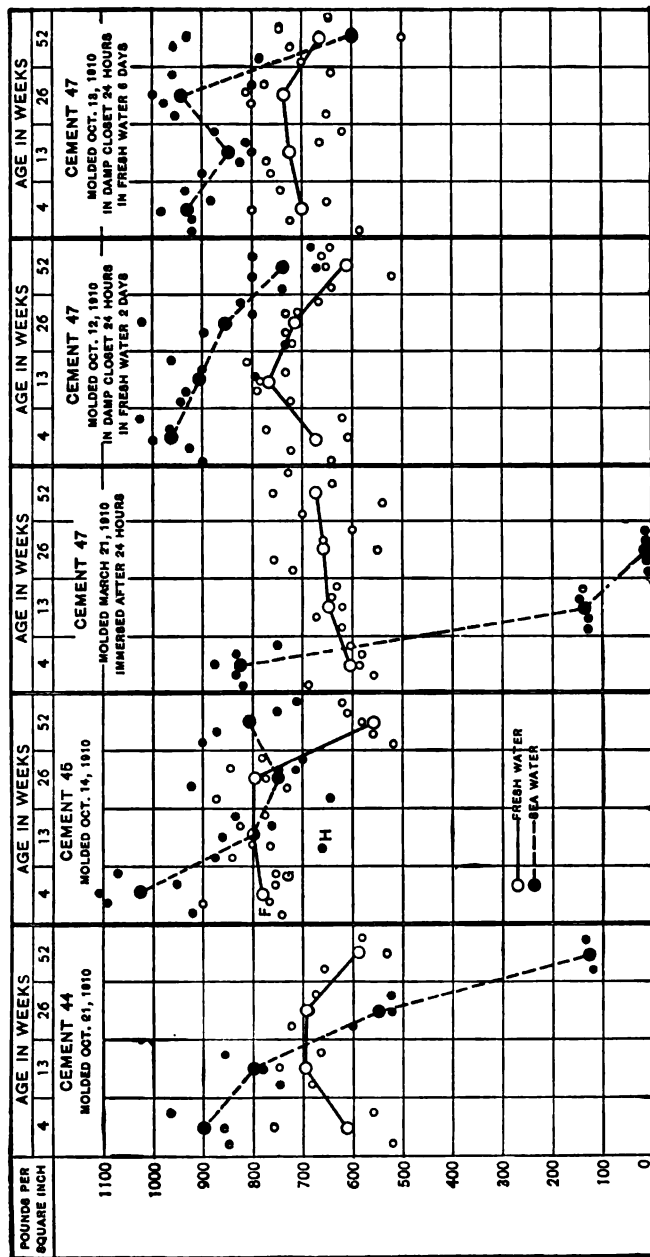


Fig. 40.—Tensile strength of neat Portland cements 44, 45, and 47, stored in damp room 24 hours before immersing. Specimens completely saturated in sea water. Cement 44 at all periods; cement 45 at 26 and 52 weeks; cement 47 molded March 21 at all periods; cement 47 molded October 12 and 13 at 52-week periods. Specimens F and G broke in grip; specimen H had void in center; cement 47, sea-water specimens, had no strength at 52 weeks

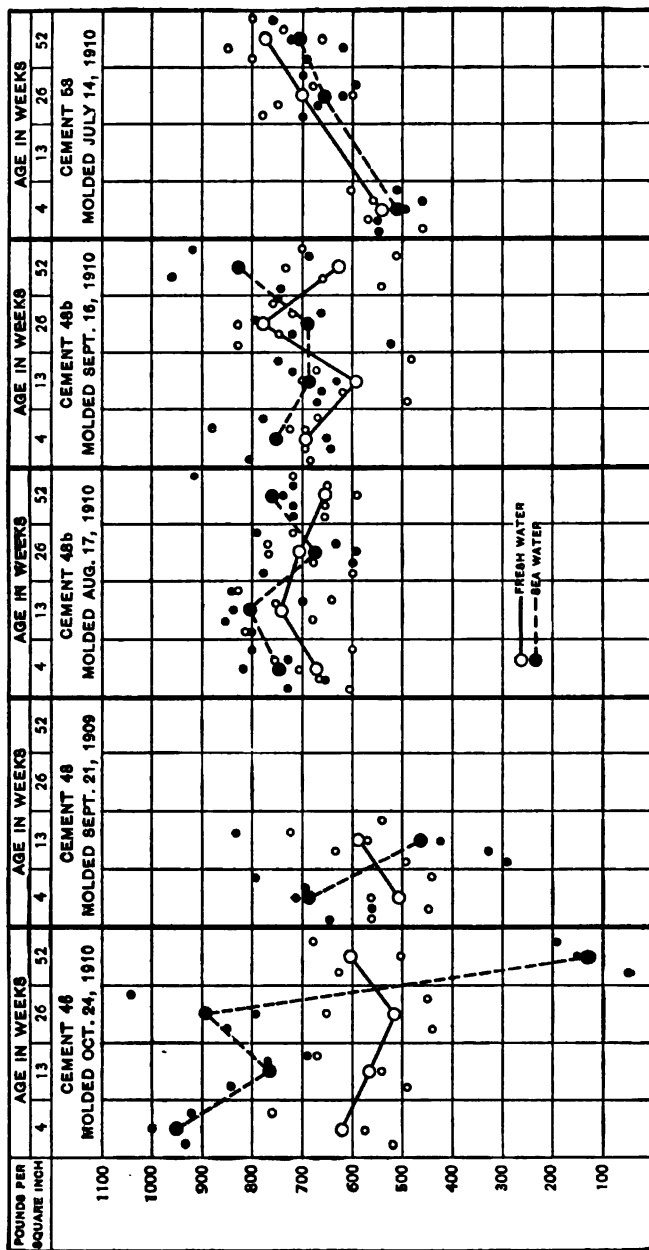


Fig. 41.—Tensile strength of neat Portland cements 46, 48, 48b, and 53, stored in damp room 24 hours before immersing. Specimens completely saturated in sea water. Cement 46 at 52 weeks; cement 48b at 13, 26, and 52 weeks; cement 53 at 26 and 52 weeks

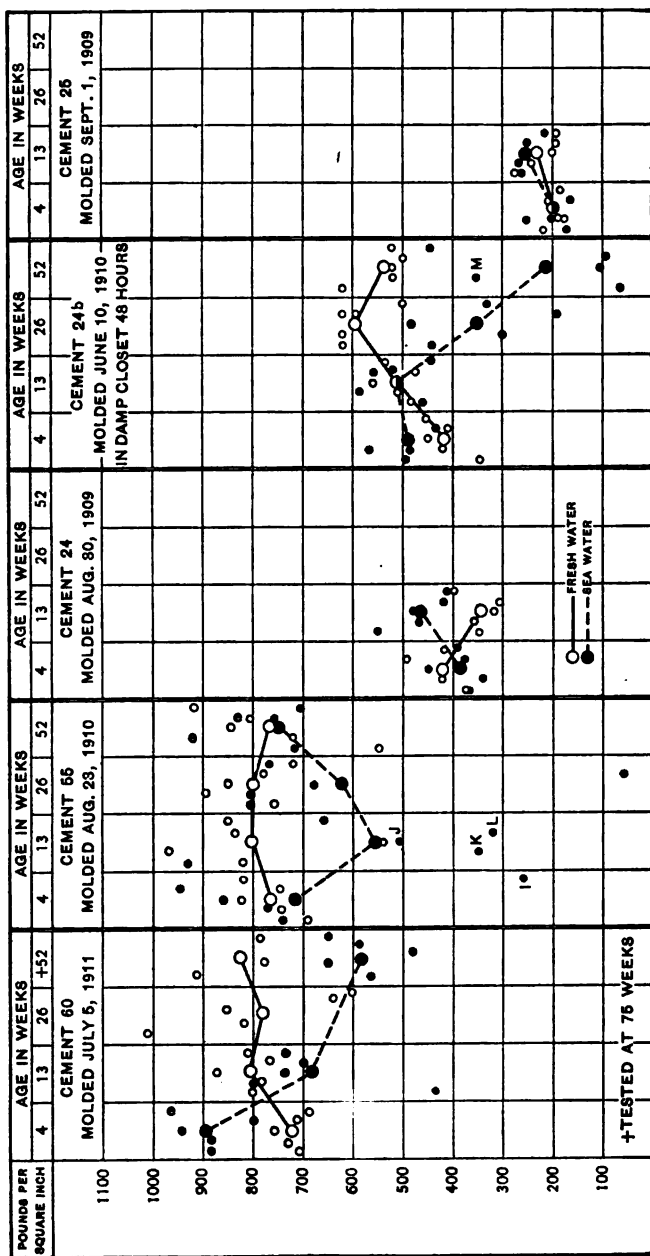


Fig. 42.—Tensile strength of neat Portland cements 60 and 55, slag cements 24 and 24b, and natural cement 25, stored in damp room 24 hours before immersing

Specimens completely saturated in sea water. Cement 60 at all periods; cement 55 at 52 weeks, and specimens I, J, K, and L; cement 24b at 52 weeks (excepting specimen M). Specimen I fractured surface covered with crystals

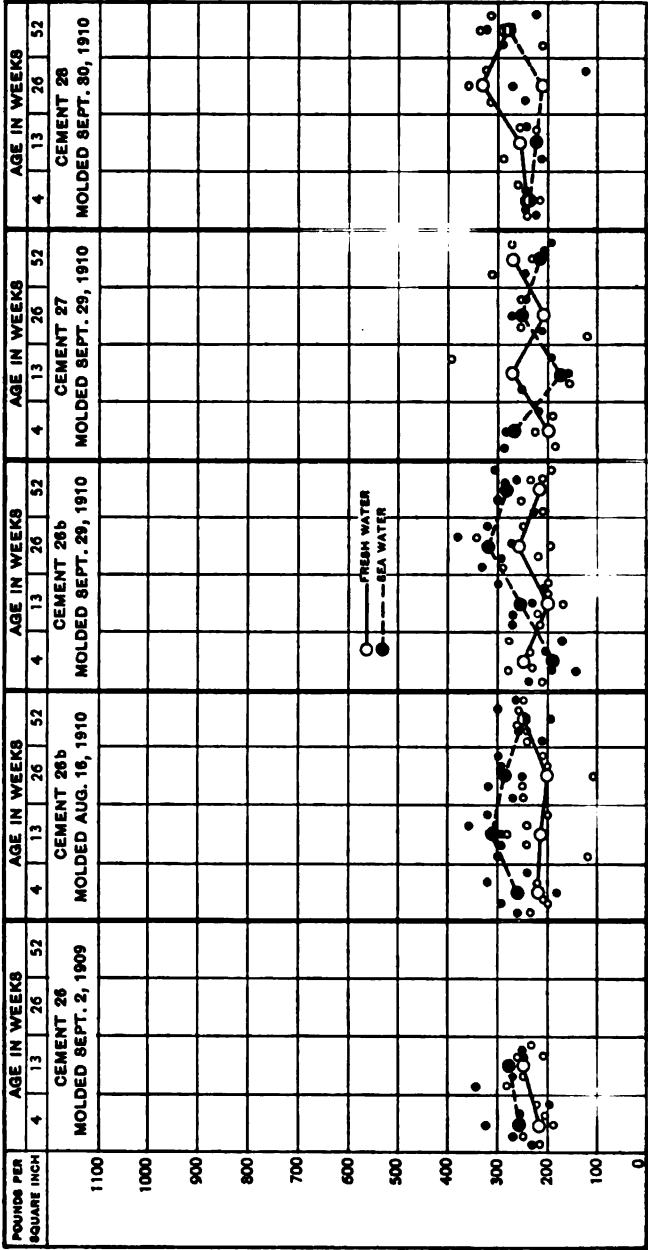


Fig. 43.—Tensile strength of neat natural cements 26, 26b, 27, and 28, stored in damp room 24 hours before immersing. Specimens completely saturated in sea water. Cement 26b at 52 weeks; cement 27 at 13, 26, and 52 weeks; and cement 28 at all periods

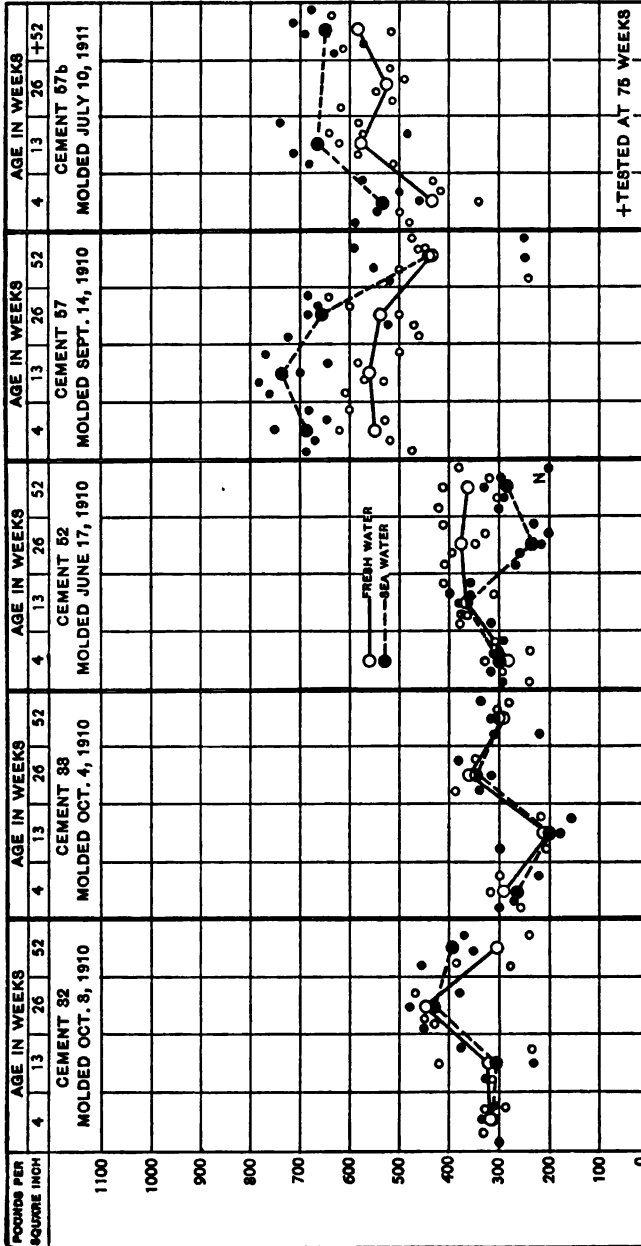


Fig. 44.—Tensile strength of neat natural cements 32, 33, and 52, and improved slag cements 57 and 57b, stored in damp room 24 hours before immersing

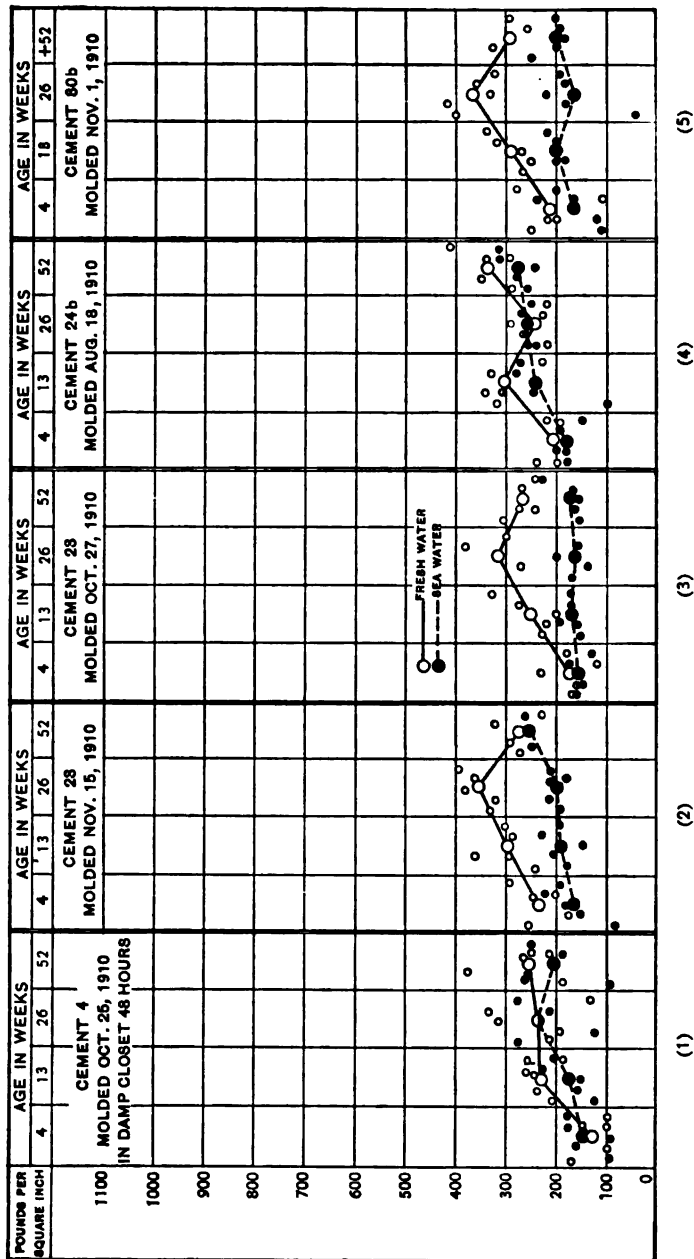


Fig. 45.—Tensile strength of 1:3 cement and standard Ottawa sand mortars, stored in damp room 24 hours before immersing. All specimens were completely saturated. White precipitate observed in interior of sea-water specimens of cement 4, except specimen P, also cement 23 and 30b

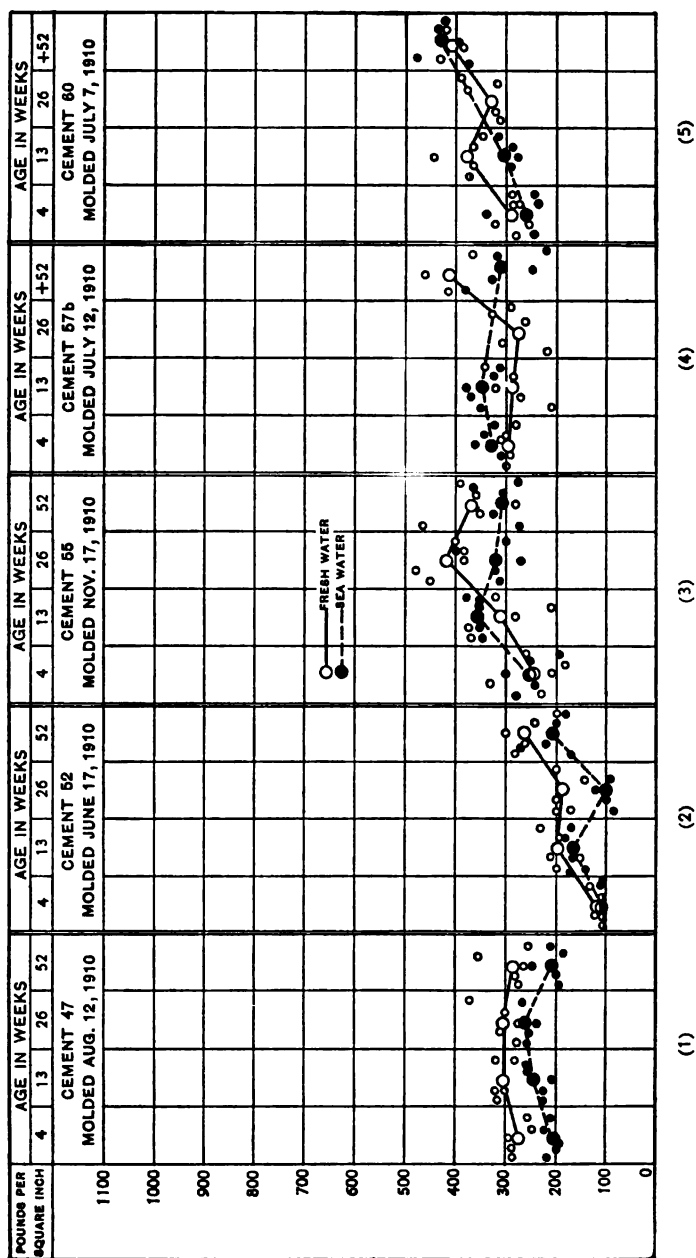


Fig. 46.—Tensile strength of 1:3 cement and standard Ottawa sand mortars, stored in damp room 24 hours before immersing. All specimens were completely saturated, and a white precipitate was observed in the interior of all sea-water specimens excepting those of cement 60.

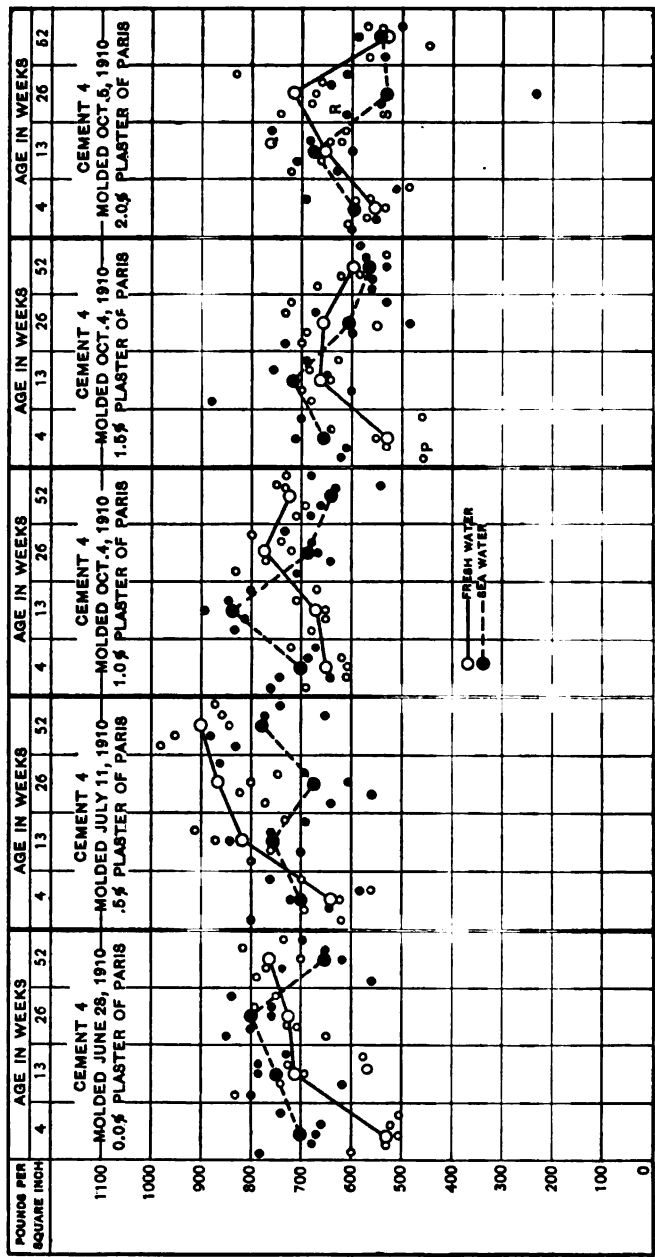


Fig. 47.—Tensile strength of neat Portland cement 4, with plaster of Paris added, stored in damp room 24 hours before immersing. Specimens completely saturated in sea water. None of cement 4 without additional plaster, all other cements at 52-week period, and cement with 2 per cent of plaster at 13 and 26 weeks (excepting specimen Q). Specimen P had void in center. Specimens R and S showed white precipitate. Specimens with 1½ per cent and 2 per cent plaster, surface peeling off at 13 weeks

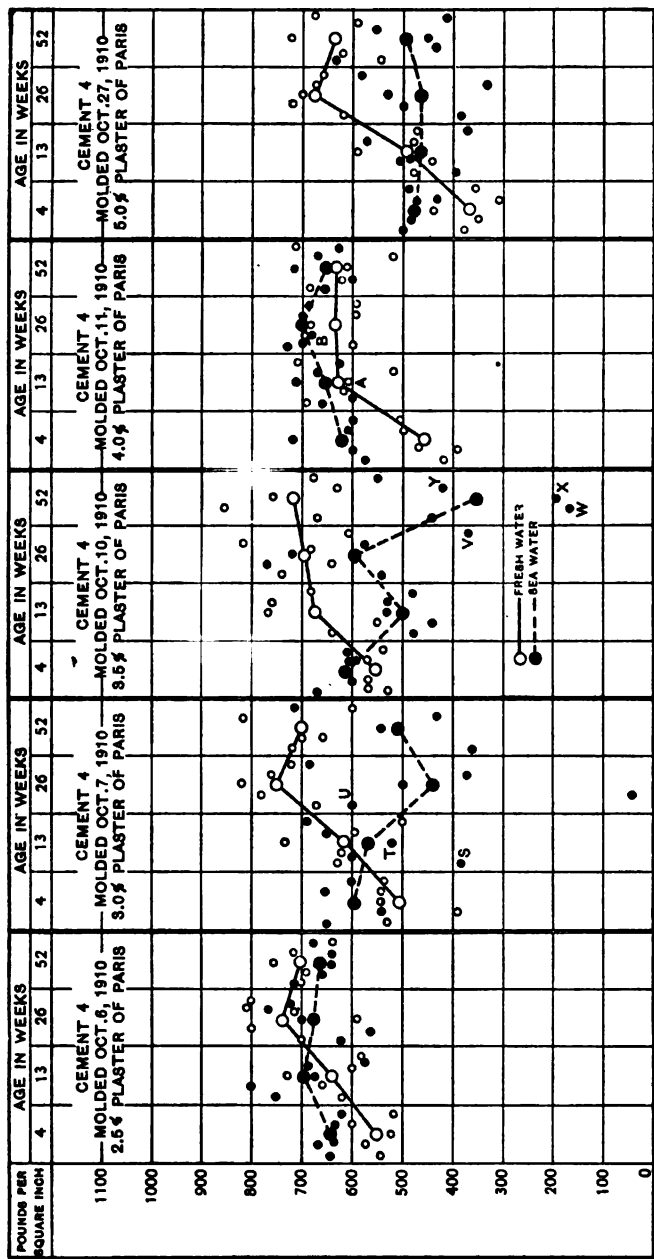


Fig. 48.—Tensile strength of neat Portland cement 4 with plaster of Paris added, stored in damp room 24 hours before immersing specimens completely saturated in sea water. All specimens at 26 and 52 weeks and specimens S and T. Surfaces peeling off of all sea-water specimens. Large crystals and white precipitate observed under loosened surfaces, also in fracture of specimens (B), (V), (W), (X), and (Y)

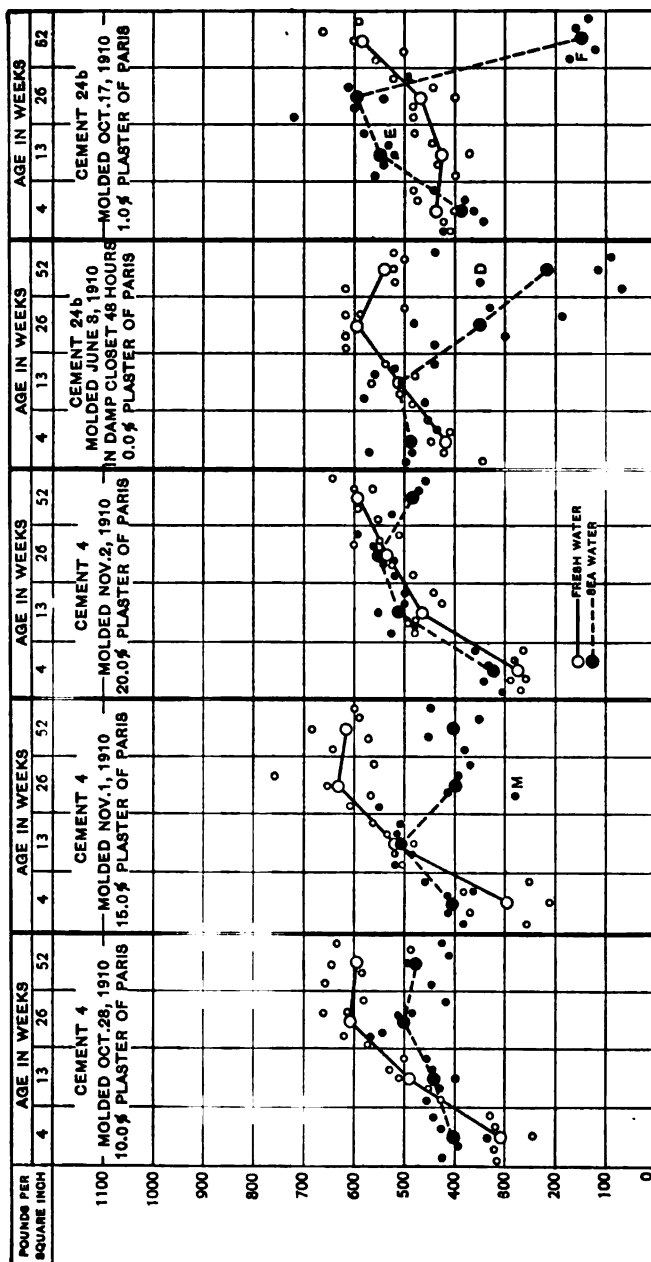


Fig. 49.—Tensile strength of neat Portland cement 4 and neat slag cement 24b, with plaster of Paris added, stored in damp room 24 hours before immersing

All specimens completely saturated in sea water excepting diagrams (3) and (5) at 4 and 13 weeks, (4) at 4, 13, and 26 weeks, and specimens (D) and (F). Crystals observed on fractured surfaces of some specimens of diagrams (1), (2), and (3) at 13 weeks and later; specimens (E) showed hair cracks on surface and corners were cracked off; specimen (M) showed large crystals on fractured surface

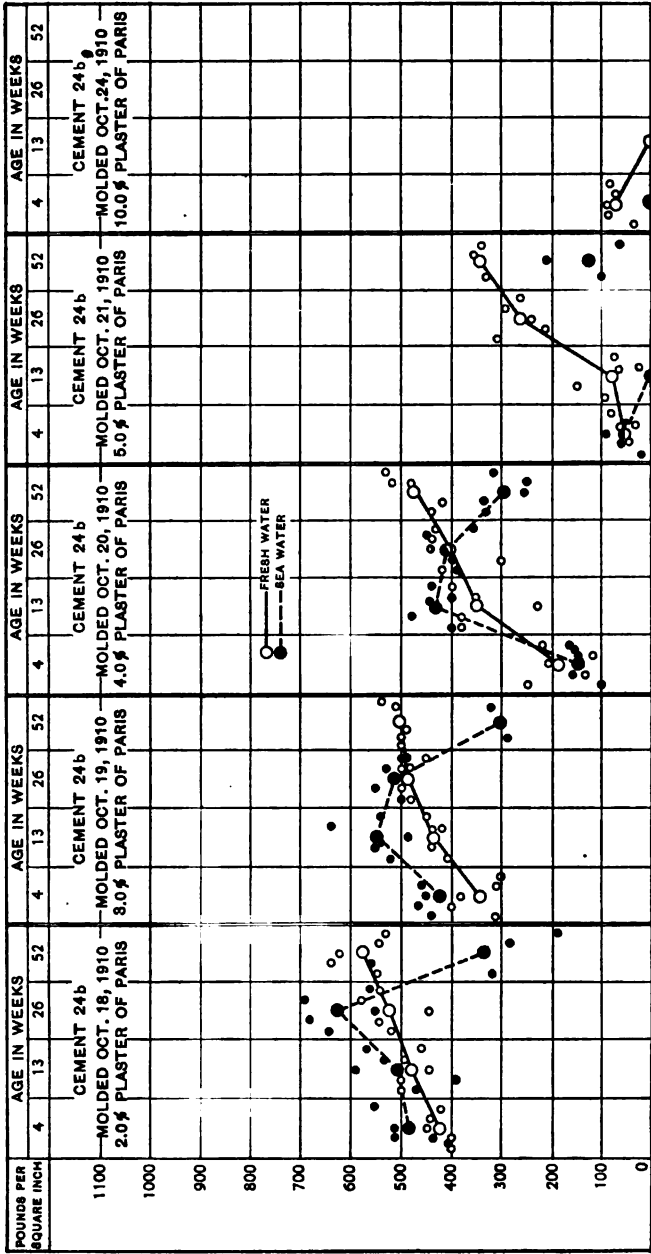


Fig. 50. — Tensile strength of neat slag cement 24b with plaster of Paris added, stored in damp room 24 hours before immersing. All specimens completely saturated in sea water excepting diagram (1) at 4 and 13 weeks and diagrams (2) and (3) at 4 weeks. Surfaces of specimens of diagrams (2) and (3) hair cracked at 13 weeks and later; specimens diagrams (4) and (5) at 4 weeks and later. Diagram (4) at 13 weeks badly swollen. Diagram (5) at 4 weeks so badly swollen and cracked they could not be tested, and fresh-water specimens also entirely disintegrated at 13 weeks

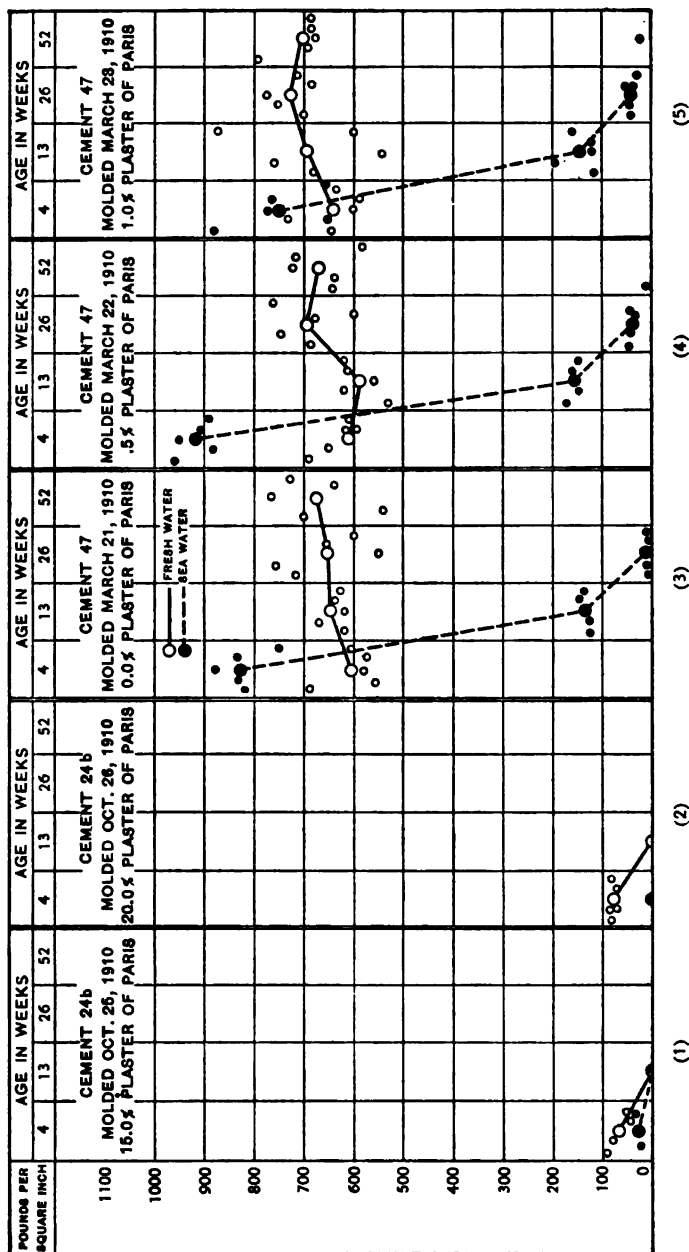


Fig. 51.—Tensile strength of neat slag cement 24b and neat Portland cement 47, with plaster of Paris added, stored in damp room 24 hours before immersing

All specimens in sea water completely saturated. Diagram (1) badly cracked and swollen at 4 weeks, and both fresh and sea water specimens were disintegrated at 13 weeks. Diagram (2), sea-water specimens disintegrated at 4 weeks and fresh-water specimens disintegrated at 13 weeks. Diagrams (3), (4), and (5), sea-water specimens, badly cracked at 52 weeks. Large crystals observed on fractured surfaces of specimens of diagrams (3) and (4) at 26 weeks, and diagram (5) at 13 weeks

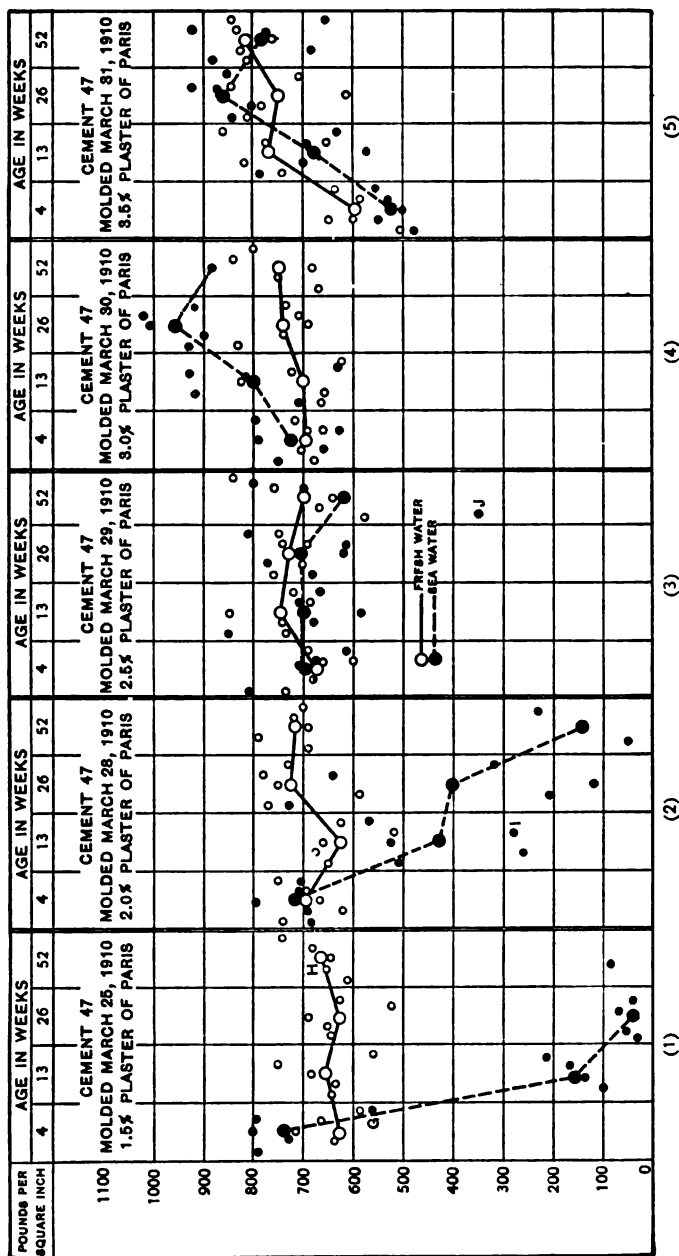


Fig. 52.—Tensile strength of neat typical Portland cement, with plaster of Paris added, stored in damp room 24 hours before immersing. All specimens in sea water completely saturated excepting diagrams (1) and (4) at 4 weeks. Diagram (1), sea-water specimens, hair cracked and swollen at 26 weeks, showed white precipitate and large crystals in fracture. Specimen (G) had void in center. Diagram (2), sea-water specimens, hair cracked and swollen at 13 weeks; also crystals and white precipitate on fractured surface. Diagram (3), sea-water specimens, hair cracked along edges at 13 weeks. Specimen (J) shows crystals on fractured surface. Diagram (4), sea-water specimens, slightly hair cracked and swollen at 26 weeks, and only one specimen tested at 52 weeks. Diagram (5), sea-water specimens, hair cracked at 4 weeks and later periods.

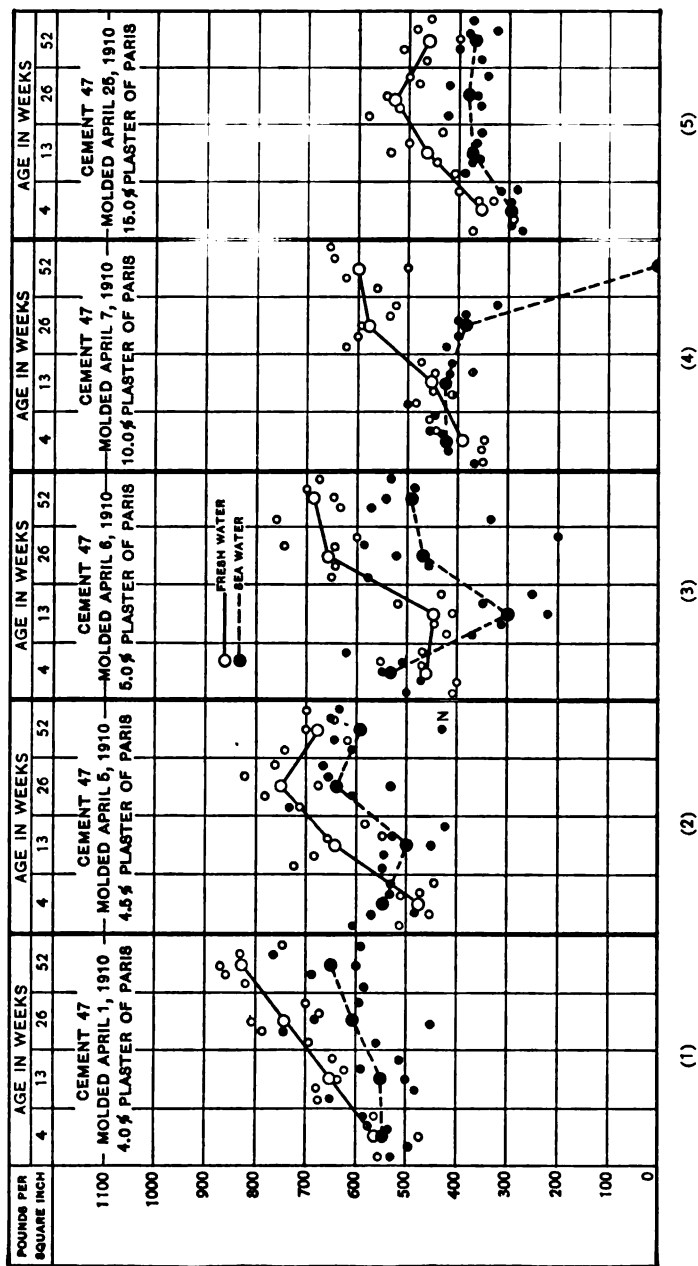


Fig. 53.—Tensile strength of neat Portland cement 47 with plaster of Paris added, stored in damp room 24 hours before immersing

All specimens were completely saturated. Diagram (1), sea-water specimens, surface hair cracked and peeling off at 13 weeks; at 26 weeks a white precipitate was observed on fractured surface; at 52 weeks crystals were observed on fractured surface. Diagrams (2) and (3), sea-water specimens, surface hair cracked and peeling off at 13 weeks; at 52 weeks crystals were observed on fractured surface. Diagram (4), sea-water specimens, hair cracked and swollen and crystals observed on fractured surface at 26 weeks; at 52 weeks specimens were found completely disintegrated. Diagram (5), sea-water specimens, hair cracked and surface peeling off at 13 weeks; at 26 weeks crystals were observed on fractured surfaces; at 52 weeks specimens badly cracked. Fresh-water specimens also slightly swollen at 52 weeks.

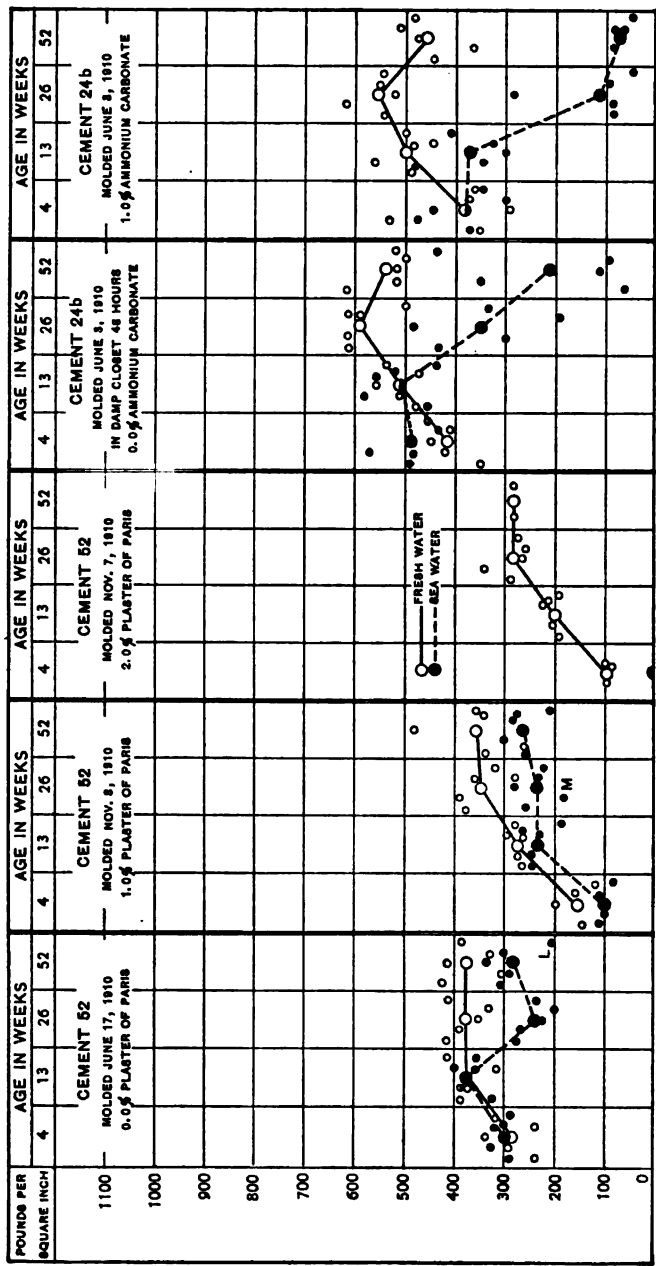


Fig. 54.—Tensile strength of neat natural cement, with plaster of Paris added, and neat slag cement with the addition of ammonium carbonate to the mixing water, stored in damp room 24 hours before immersing

All specimens were completely saturated excepting diagram (4) at 4, 13, and 26 weeks. Diagram (1), surfaces of sea-water specimens, peeling off at 13 weeks. Specimen (L) had void in center. Diagram (2), surfaces of sea-water specimens, hair cracked and slightly swollen at 4 weeks. Specimen (M) badly swollen. Diagram (3), sea-water specimens, totally disintegrated after 24 hours immersion. Fresh-water specimens also cracked and swollen

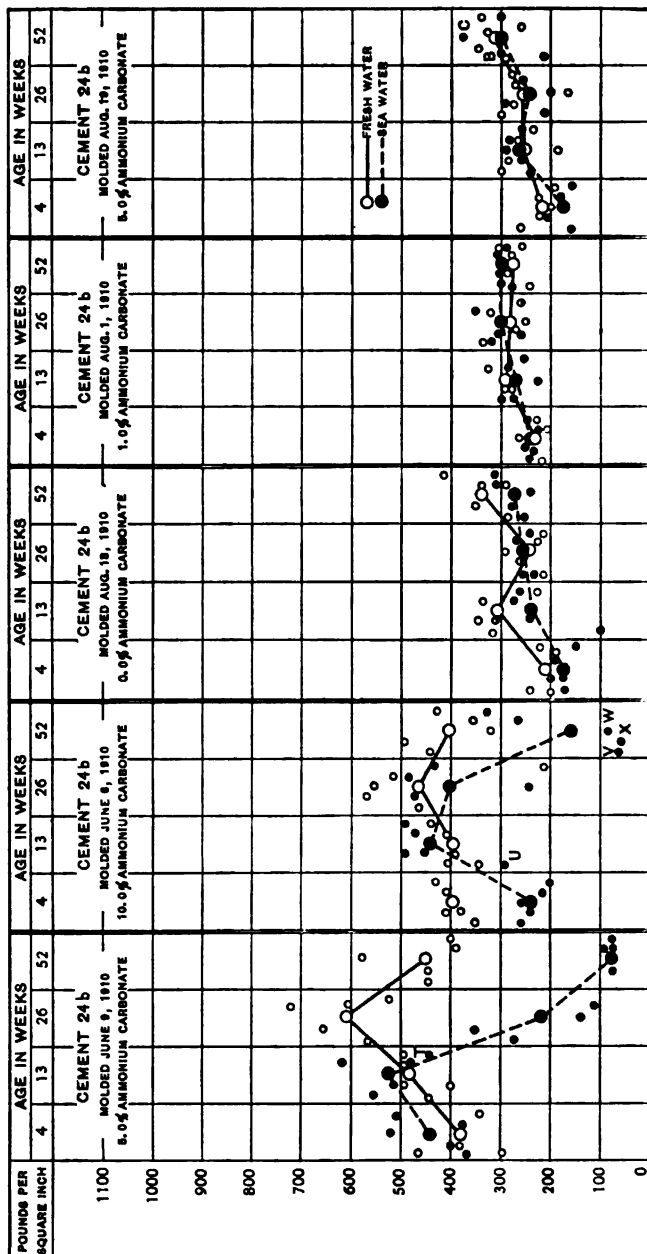


Fig. 55.—Tensile strength of neat and 1:3 slag cement standard Ottawa sand mortar, with ammonium carbonate added to the mixing water, stored in damp room 24 hours before immersing

All specimens were completely saturated. Diagram (1), 52-week sea-water specimens, slightly cracked. Specimens (T) and (U) had void in center. White precipitate observed in 52-week sea-water specimens of diagrams (4) and (5)

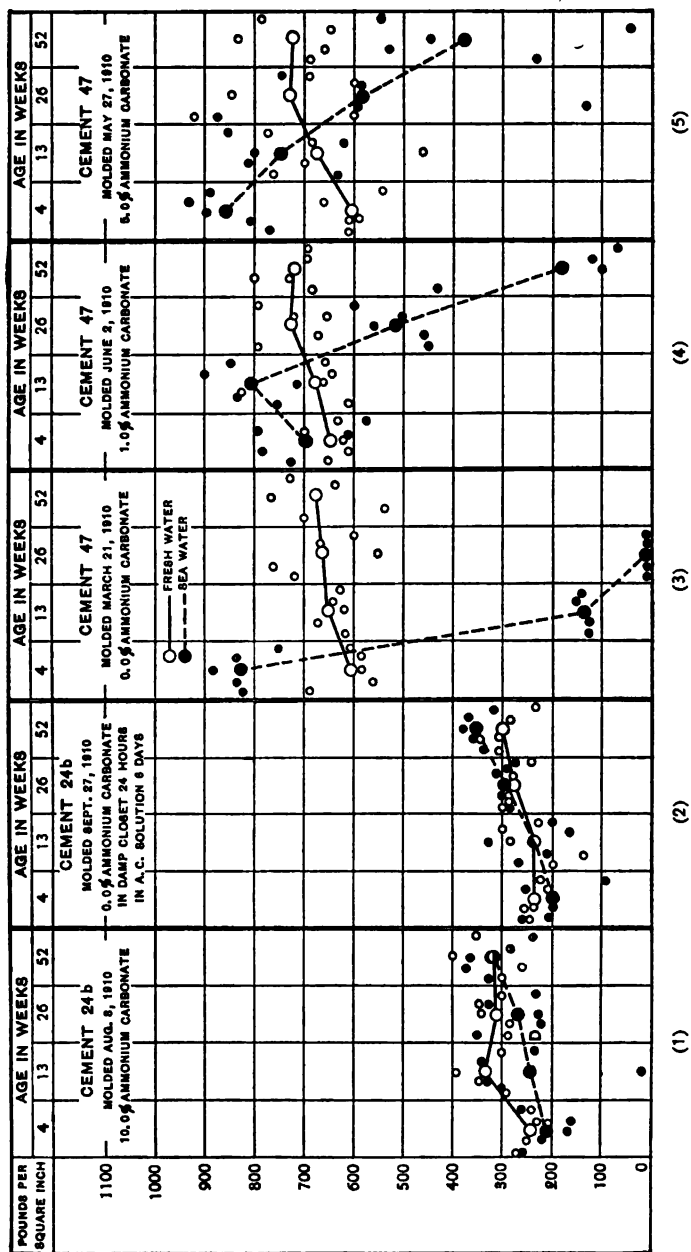


Fig. 56.—Tensile strength of 1:3 slag cement standard Ottawa sand mortar with ammonium carbonate added to the mixing water and similar mortar briquettes placed in ammonium carbonate solution. Results of tests of Portland cement 47 with ammonium carbonate added to the mixing water, stored in damp room 24 hours before immersing

All sea-water specimens completely saturated excepting diagram (5) at 4 weeks. Diagram (1) white precipitate in interior sea-water specimens at 13 weeks. Diagram (3) fractured surfaces of sea-water specimens at 26 weeks covered with large crystals. Diagram (5), sea-water specimens, hair cracked and surface peeling off at 13 weeks

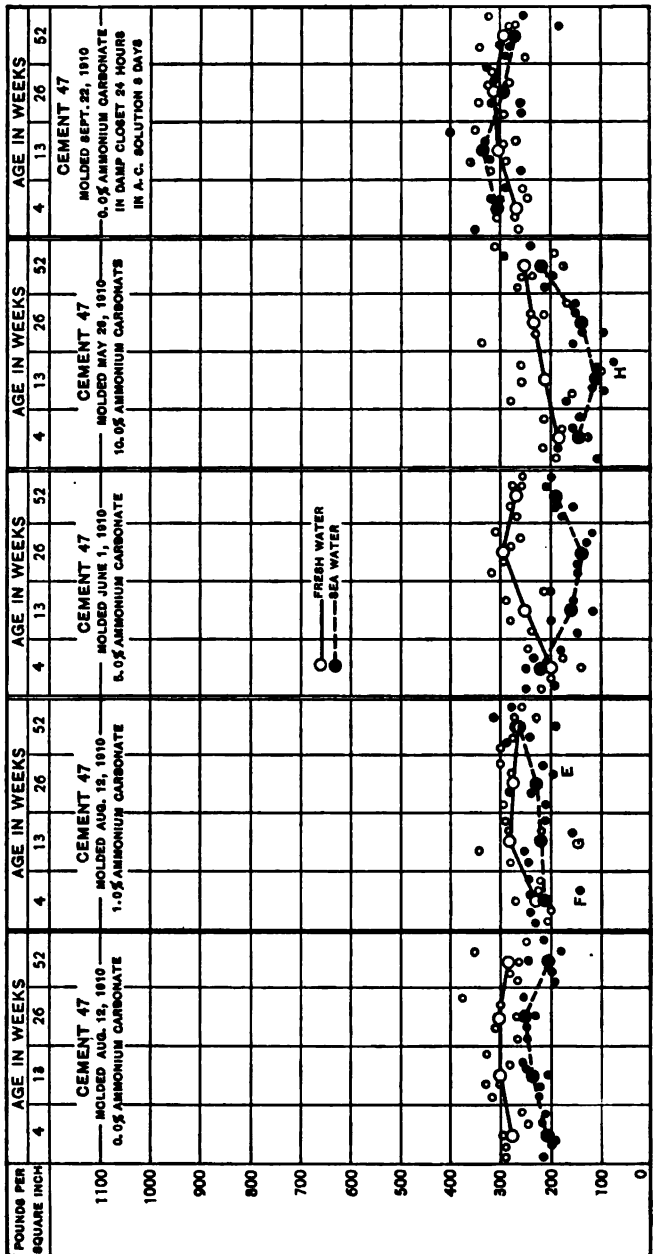


Fig. 57.—Tensile strength of 1:3 Portland cement standard Ottawa sand mortar with ammonium carbonate added to the mixing water, stored in damp room 24 hours before immersing

All specimens were completely saturated. Diagrams (1), (2), (3), and (4) white precipitate observed in interior of sea-water specimens at 4 weeks and later periods, and in specimens of diagram (5) at 26 and 52 weeks. The precipitate was very heavy in specimens (F), (G), and (E)

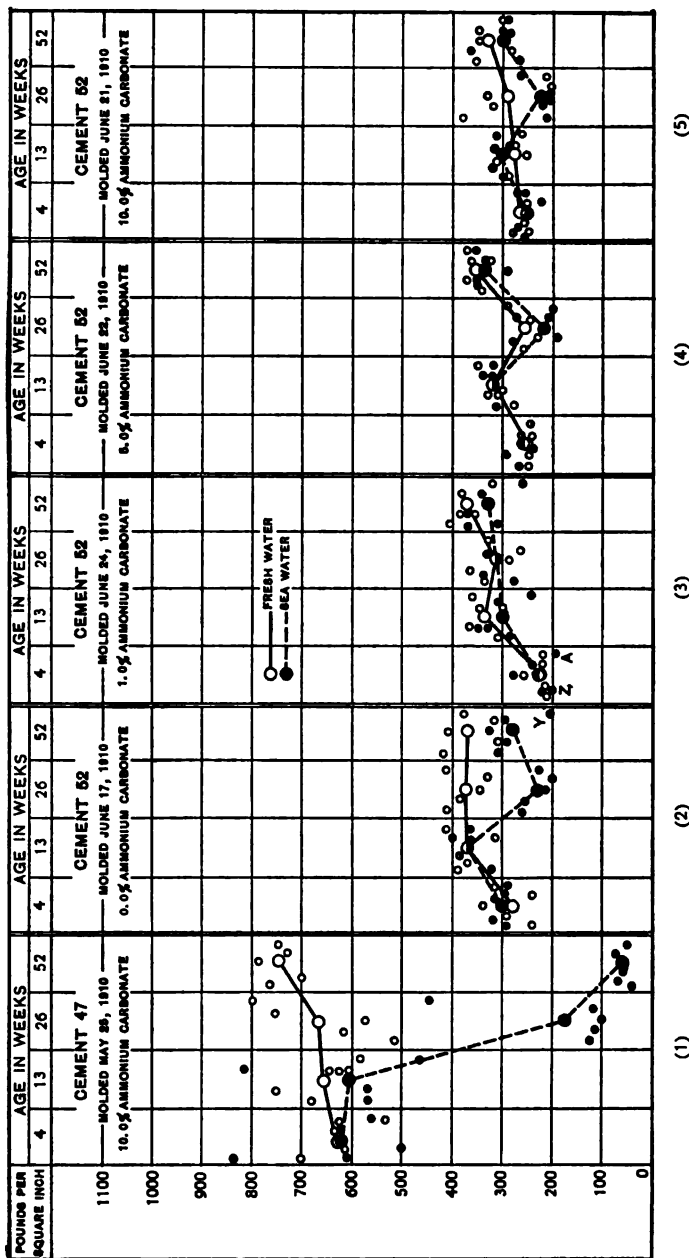


Fig. 58.—Tensile strength of neat Portland cement 47 and natural cement 52 with ammonium carbonate added to the mixing water; stored in damp room 24 hours before immersing

All specimens were completely saturated. Diagram (1), sea-water specimens, slightly hair cracked at 13 weeks and crystals observed in fractures at 52 weeks. Diagram (2), surface peeling off of sea-water specimens at 13 weeks. Void in center of specimen (Y) and (A). Specimen (Z) defective

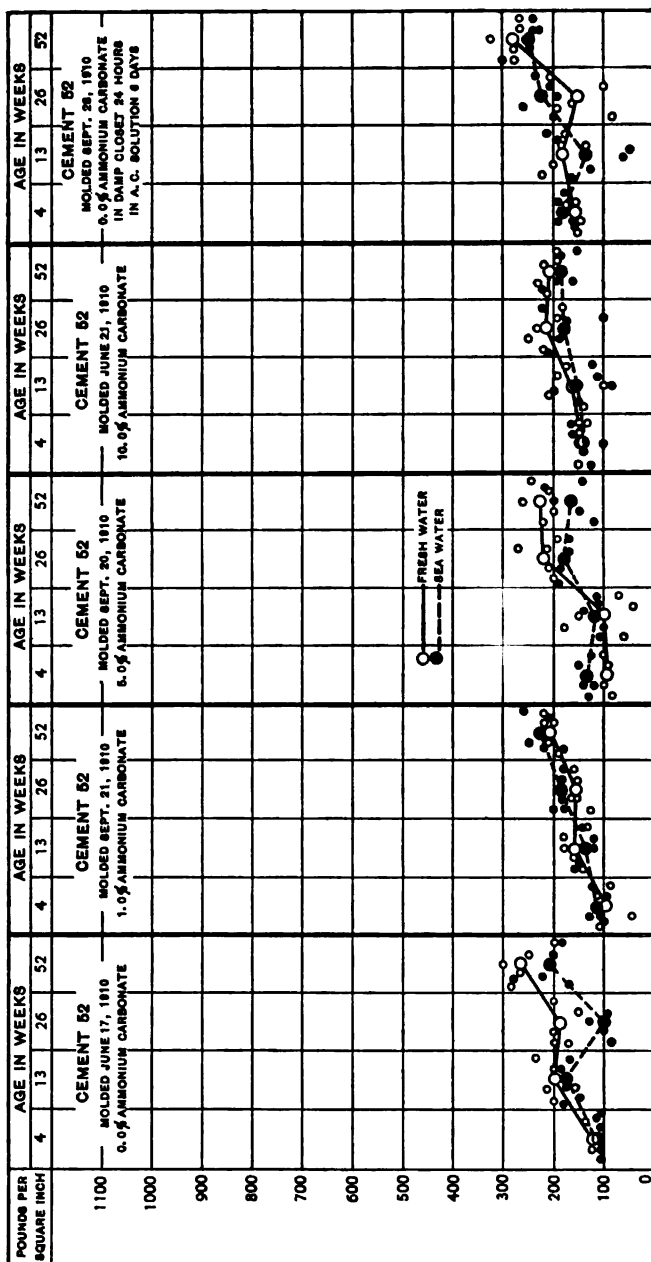


Fig. 59.—Tensile strength of 1:3 natural cement standard Ottawa sand mortar with ammonium carbonate added to the mixing water; stored in damp room 24 hours before immersing

All specimens were completely saturated. White precipitate observed in interior of all sea-water specimens excepting those of diagram 5

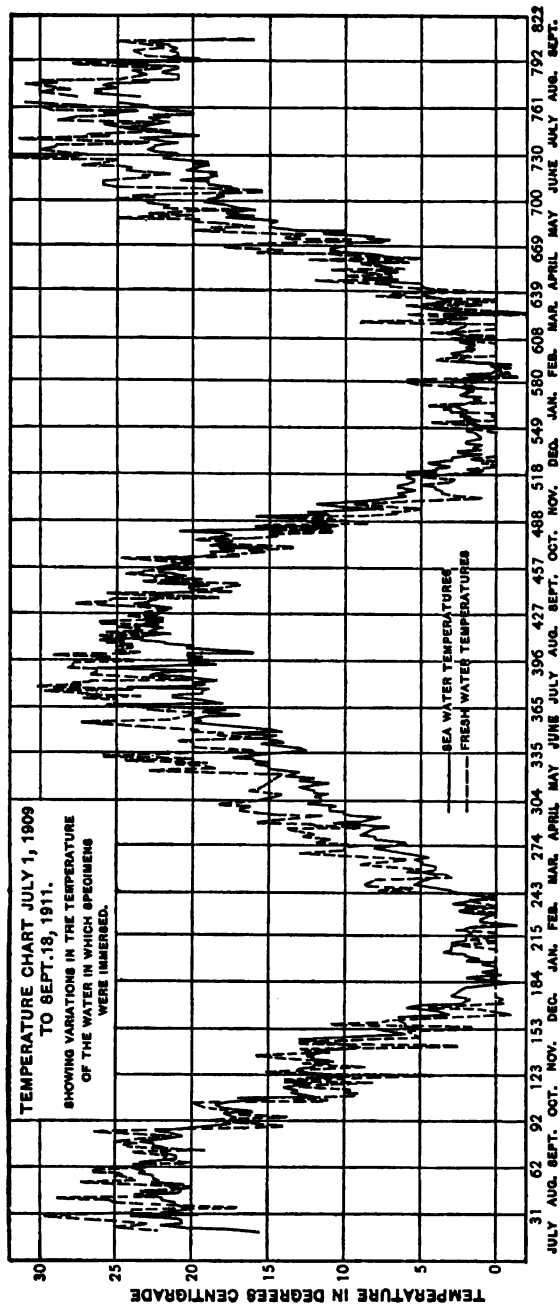


Fig. 60

XI. SUMMARY

The conclusions must be limited by the scope of this investigation and since the physical tests reported cover a period of exposure not exceeding $3\frac{1}{2}$ years the conclusions should be considered as somewhat tentative.

1. Portland cement mortar or concrete, if porous, can be disintegrated by the mechanical forces exerted by the crystallization of almost any salt in its pores, if a sufficient amount of it is permitted to accumulate and a rapid formation of crystals is brought about by drying; and as larger crystals are formed by slow crystallization, there would be obtained the same results on a larger scale, but in greater time if slow drying were had. Porous stone, brick, and other structural materials are disintegrated in the same manner. Therefore in alkali regions where a concentration of salts is possible, a dense nonporous surface is essential.

2. While in the laboratory a hydraulic cement is readily decomposed if intimately exposed to the chemical action of various sulphate and chloride solutions, field inspection indicates that in service these reactions are much retarded if not entirely suspended in most cases, due probably to the carbonization of the lime of the cement near the surface or the formation of an impervious skin or protective coating by saline deposits.

3. Properly made Portland cement concrete, when totally immersed, is apparently not subject to decomposition by the chemical action of sea water.

4. While these tests indicated that Portland-cement concrete exposed between tides resisted chemical decomposition as satisfactorily as the totally immersed concrete, it is felt that actual service conditions were not reproduced, and therefore further investigation is desirable.²⁸

5. It is not yet possible to state whether the resistance of cements to chemical disintegration by sea water is due to the

²⁸ In service the concrete extends from the sea bottom to a point above high tide, where the wall or pile would always be exposed to the atmosphere. With this condition the sea water could be drawn up the wall by capillarity, the moisture evaporating and leaving the salts, which would become concentrated, and thus possibly cause disintegration, especially if mixture is porous. An additional series of tests is now being made in which short piles 7 feet in length are being placed in sea water so that a feet of the center portion will be exposed to the atmosphere. After various periods of exposure the piles will be sawed and the various sections tested for elastic properties and compressive strength.

superficial formation of an impervious skin or coating, which is subsequently assisted by the deposition of shells and moss forming a protective coating, or by the chemical reaction of the sea salts with the cement forming a more stable compound without disintegration of the concrete, or by a combination of both of these phenomena.

6. Marine construction, in so far as the concrete placed below the surface of the water is concerned, would appear to be a problem of method rather than materials, as the concrete sets and permanently hardens as satisfactorily in sea water as in fresh water or in the atmosphere, if it can be placed in the forms without undue exposure to the sea water while being deposited.

7. Natural, slag, and other special cements tested in concrete mixtures showed normal increase in strength with age both in sea water and in fresh water.

8. In the form of neat briquettes most of the Portland cements of high iron content, several of the cements of high or normal alumina content and one special slag cement did not show any marked difference in tensile strength whether exposed to fresh or sea water for all periods up to two years. Other cements of various compositions showed signs of disintegration after a few weeks.

9. All cements resisted disintegration in sea water better in mortar mixtures than in the form of neat briquettes. In most cases the mortar briquettes had normal strength up to 2 years exposure.

10. The physical qualities of the cement, which depend essentially upon the method of manufacture, would seem to determine its resistance to decomposition when brought into intimate contact with the sulphate and chloride solutions.

11. Contrary to the opinion of many, there is no apparent relation between the chemical composition of a cement and the rapidity with which it reacts with sea water when brought into intimate contact.

12. Tricalcium-sulpho-aluminate could not be formed, and therefore disintegration could not result from this cause.

13. In the presence of sea water or similar sulphate—chloride solutions:

(a) The most soluble element of the cement is the lime. If the lime of the cement is carbonated it is practically insoluble.

(b) The quantity of alumina, iron, or silica present in the cement does not affect its solubility.

(c) The magnesia present in the cement is practically inert.

(d) The quantity of SO_3 present in the cement up to 1.75 per cent does not affect its solubility, but a variation in the quantity present may affect its stability by affecting its rate of hardening.

14. The change which takes place in sea water when brought into intimate contact with the cement is as follows:

(a) The magnesia is precipitated from the sea water in direct proportion to the solubility of the lime of the cement.

(b) The sulphates are the most active constituents of the sea water and are taken up by the cement. Their action is accelerated in the presence of chlorides. No definite sulphate compound was established.

(c) The quantity of chlorine and sodium taken up by the cement is so small that no statement can be made as to the existence of any definite chloride or sodium compound formed with the cement.

15. The SO_3 added to a cement in the plaster to regulate the time of set is chemically fixed so that it will not go into solution when the cement is brought into intimate contact with distilled water.

16. Metal reinforcement is not subject to corrosion if embedded to a depth of 2 inches or more from the surface of well-made concrete.

WASHINGTON, November 1, 1912.

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TABLE 1
Analyses of Incrustations, Efflorescence, and Typical "Alkali" from Various Localities

Source of sample	Character of sample	Percentages of components obtained by analyses													
		Silica (SiO ₂)	Alumina (Al ₂ O ₃)	Iron oxide (Fe ₂ O ₃)	Lime (CaO)	Magnesia (MgO)	Soda (Na ₂ O)	Potash (K ₂ O)	Sulphuric anhydride (SO ₃)	Chlorine (Cl)	Carbon dioxide (CO ₂)	Organic and combined water	Insoluble (HCl) (1-1)	Total	Oxygen per chloride
Uncompahgre, Colo., Station 167+50.....	Incrustation.....	15.96	1.27	62.51	5.50	0.46	0.06	0.17	1.34	.....	1.79	11.03	0.17	100.26	.....
Uncompahgre, Colo., Station 168+50.....	do.....	16.52	1.34	59.74	5.67	0.47	.16	.39	1.77	.....	1.68	11.93	.25	99.96	.....
Uncompahgre, Colo., Station 169+50.....	do.....	16.99	1.94	58.85	5.24	.45	.10	.19	1.45	.....	1.56	12.11	1.40	100.25	.....
Twiss, Wash., canal lining, Station 86.....	Efflorescence.....	1.62	1.04	.84	2.57	.33	35.99	.65	4.94	0.04	25.07	6.29	20.62	100.00	.....
Belle Fourche, S. Dak., siphon site, south canal.....	do.....	1.11	.92	.75	38.09	6.45	1.45	1.07	9.27	.06	28.21	4.27	8.36	100.01	0.01
Belle Fourche, S. Dak., south canal.....	Efflorescence from shale.....	.89	2.24	.51	24.79	1.11	1.13	.23	7.79	.02	15.47	4.56	42.77	100.01	.01
Do.....	Efflorescence.....	.78	.93	1.36	13.94	2.07	5.85	.41	15.41	.12	9.57	5.06	42.73	100.03	.03
Belle Fourche, S. Dak., Brule lateral, south canal.....	do.....	.72	1.67	.81	1.28	6.59	16.82	.43	35.34	.36	.37	3.11	32.58	100.08	.08
Belle Fourche, S. Dak., Station 200, south canal.....	do.....	.59	.95	.67	1.62	9.81	14.35	.30	39.67	.05	.38	1.22	30.40	100.01	.01
Belle Fourche, S. Dak., Station 100, south canal.....	do.....	.51	1.07	.66	2.39	5.51	15.55	.49	31.49	.14	.61	7.75	33.86	100.03	.03
Belle Fourche, S. Dak., Station 299, north canal.....	do.....	.55	2.59	1.39	2.62	6.07	8.99	.63	27.12	.09	.11	3.16	46.70	100.02	.02
Belle Fourche, S. Dak., Spillway No. 2, north canal.....	do.....	.83	1.35	.98	5.06	5.91	21.88	.79	40.53	.53	2.50	3.47	16.29	100.12	.12
Belle Fourche, S. Dak., north canal.....	do.....	1.95	2.76	1.25	8.84	7.24	7.61	.21	26.21	.19	2.17	3.99	37.61	100.04	.04
Do.....	do.....	.57	1.56	.50	3.32	5.77	9.32	1.00	25.44	.13	1.75	3.15	47.72	100.03	.03
Belle Fourche, S. Dak., north conduit.....	do.....	.85	1.19	1.16	2.43	4.57	8.86	.56	22.44	.44	.50	5.10	51.99	100.09	.09
Do.....	do.....	.78	.97	.81	2.39	5.63	11.81	.64	26.87	.13	.16	4.97	41.86	100.02	.02
Belle Fourche, S. Dak., main canal.....	do.....	.73	2.18	1.19	2.24	4.95	10.96	.66	25.96	.14	.75	3.46	46.81	100.03	.03
Billings, Mont., bank building.....	Disintegrated sandstone.....	.26	.37	.44	4.94	10.89	16.51	1.60	42.65	3.72	.94	4.68	13.84	100.84	.84
Sun River, Mont., canal bank.....	Efflorescence.....	.42	.47	.11	1.59	13.94	17.77	.82	52.07	.30	.59	2.22	9.77	100.07	.07
Sun River, Mont., culvert outlet.....	do.....	1.23	.44	.96	5.12	8.62	10.47	2.80	34.30	.18	3.06	7.71	25.15	100.04	.04

Sun River, Mont., canal bottom.	do.	.41	.52	.49	4.93	9.35	16.02	.57	39.48	.68	3.62	3.31	20.77	100.15	.15
Sun River, Mont., outside bank.	do.	.63	.96	.69	2.37	13.13	11.68	1.08	40.72	.17	2.17	7.69	19.15	100.04	.04
Sun River, Mont., around Pier 3.	do.	.61	.97	.74	2.56	5.98	13.16	1.63	28.93	.17	2.68	6.54	36.05	100.04	.04
Sun River, Mont., bottom of Simms Creek.	do.	.63	1.69	.75	5.18	5.92	15.00	.63	29.15	.29	2.94	6.04	31.85	100.07	.07
Great Falls, Mont., courthouse.	Disintegrated sandstone.	.72	.77	.63	3.02	7.91	7.31	2.54	28.48	.29	1.52	4.40	42.48	100.07	.07
Great Falls, Mont., conduit.	Efflorescence.	.27	.54	.30	5.92	7.29	12.61	7.05	36.88	3.14	2.61	6.43	17.67	100.71	.71
Great Falls, Mont., brick sewer, Sixth Street.	do.	.60	.50	.46	3.93	7.02	21.86	1.18	43.52	.93	.86	7.94	11.91	100.21	.21
Great Falls, Mont., manhole No. 1, Sixth Street.	do.	.43	.40	.43	2.29	.00	36.57	1.16	49.81	.09	1.06	.02	7.26	100.02	.02
Great Falls, Mont., manhole No. 2, Sixth Street.	do.	.33	.23	.30	1.35	.00	40.58	.90	53.95	.05	.52	.35	1.45	100.01	.01
Shoshone, Wyo., Garland Canal.	do.	.43	.33	.30	3.63	.14	37.97	.65	50.79	.21	1.96	1.40	2.24	100.05	.05
Do.	do.	.08	.11	.04	1.72	1.16	37.76	1.36	41.62	.77	.86	1.46	3.23	100.17	.17
Shoshone, Wyo., Corbett Tunnel.	do.	.67	.71	.76	2.32	1.93	26.32	1.06	39.83	.11	.77	1.56	23.98	100.02	.02
Shoshone, Wyo., spillway.	do.	.68	.70	.99	5.86	.71	30.04	.73	39.97	.77	3.42	3.18	13.72	100.17	.17
Shoshone, Wyo., concrete conduit.	do.	.41	.66	.58	2.50	2.24	23.48	.98	36.44	1.22	.77	2.46	28.53	100.27	.27
Hunter, Mont., main canal.	do.	.43	1.17	1.11	4.97	12.85	1.61	.21	31.68	.14	1.29	9.68	34.89	100.03	.03

TABLE 2
Analyses of the Cements Used in the Chemical Investigation

Constituent	Unset	Set
	Per cent	Per cent
SiO ₂	21.45	18.78
Al ₂ O ₃	8.44	6.90
Fe ₂ O ₃	1.72	1.73
CaO.....	63.85	55.61
MgO.....	2.77	2.31
SO ₃.....	.26	.22
Na ₂ O.....	.48	.41
K ₂ O.....	.42	.36
CO ₂.....	.15	1.98
Ignition loss.....	.55	11.70
	100.09	100.00

TABLE 3
Total Percentage of Silica Removed by the Sodium Carbonate Series of Solutions

Solution used	Cement used	Total percentage removed at end of following periods, in weeks						
		1	2	3	4	6	8	9
Sodium carbonate (Na ₂ CO ₃).....	Unset.....	0.00	7.8	.....	12.5	17.2	22.8	.....
Sodium carbonate-sodium chloride (Na ₂ CO ₃ -NaCl).....	do.....	.00	2.6	.....	7.8	12.4	14.9	.....
Sodium carbonate-sodium sulphate (Na ₂ CO ₃ -Na ₂ SO ₄).....	do.....	.00	2.3	.....	7.4	11.6	17.2	.....
Sodium carbonate (Na ₂ CO ₃).....	Set.....	5.3	12.9	18.6	24.2	28.1	.....	30.5

Solution used	Cement used	Total percentage at end of following periods, in weeks							
		10	12	16	20	26	32	38	44
Sodium carbonate (Na ₂ CO ₃).....	Unset.....	27.5	29.9	32.2	34.4	36.8	39.1	41.6	42.8
Sodium carbonate-sodium chloride (Na ₂ CO ₃ -NaCl).....	do.....	17.2	22.4	25.6	29.6	33.3	35.2	36.6	37.7
Sodium carbonate-sodium sulphate (Na ₂ CO ₃ -Na ₂ SO ₄).....	do.....	22.8	28.4	31.6	36.3	39.6	43.3	45.7	47.1
Sodium carbonate (Na ₂ CO ₃).....	Set.....	.....	33.4	.....	.....	.....	.....	.....	.....

TABLE 4

Comparison of the Analyses of the Residues Obtained as a Result of the Action of Various Solutions upon the Unset Cement with the Residues Calculated from the Changes in the Composition of the Solutions Observed after they had been Withdrawn from the Cement

Solution used	Method ^a	Percentages of components obtained by analyses—										
		SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Cl	Na ₂ O	K ₂ O	CO ₂	Total
Sodium chloride (NaCl).....	A	35.16	13.83	2.81	0.67	39.45	0.43	5.41	1.61	0.69	0.25	101.21
Sodium chloride—Sodium sulphate (NaCl—Na ₂ SO ₄).....	B	36.42	14.27	3.35	.98	39.75	.11	5.37	.44	.08	.29	101.26
Sodium chloride—Sodium carbonate (NaCl—Na ₂ CO ₃).....	A	33.35	13.12	2.67	3.03	38.72	5.68	3.58	2.77	.66	.23	100.81
Sodium chloride—Sodium carbonate (NaCl—Na ₂ CO ₃).....	B	31.24	11.46	2.69	2.94	39.21	6.52	4.02	1.92	.31	.82	100.90
Sodium chloride—Calcium chloride (NaCl—CaCl ₂).....	A	31.24	11.46	1.23	45.12	2.00	.19	.....	2.58	.08	32.64	100.00
Sodium chloride—Calcium chloride (NaCl—CaCl ₂).....	B	8.89	5.20	1.69	46.12	2.39	.07	.49	1.97	.20	33.09	100.11
Sodium chloride—Magnesium chloride (NaCl—MgCl ₂) ^b	A	32.18	12.66	2.58	2.48	41.36	.39	7.20	1.92	.63	.22	101.62
Sodium chloride—Magnesium chloride (NaCl—MgCl ₂) ^b	B	32.96	12.18	3.08	2.42	40.74	.18	6.11	1.78	.03	1.90	101.38
Sodium chloride—Magnesium sulphate (NaCl—MgSO ₄).....	A	24.19	9.50	1.95	11.32	46.63	.97	3.60	2.01	.47	.17	100.81
Sodium chloride—Magnesium sulphate (NaCl—MgSO ₄).....	B	25.25	8.16	2.30	11.18	44.93	.61	4.63	1.32	Tr.	2.63	101.01
Sodium sulphate (Na ₂ SO ₄).....	A	35.14	13.82	2.82	1.72	37.30	4.52	2.13	2.09	.69	.76	100.48
Sodium sulphate—Sodium carbonate (Na ₂ SO ₄ —Na ₂ CO ₃).....	A	35.65	13.12	2.38	2.24	37.30	4.80	2.62	1.40	.31	.76	100.58
Sodium sulphate—Sodium carbonate (Na ₂ SO ₄ —Na ₂ CO ₃).....	B	8.31	5.21	1.25	46.73	2.03	.19	.....	2.33	.21	33.64	100.00
Sodium sulphate—Magnesium chloride (Na ₂ SO ₄ —MgCl ₂).....	A	8.04	4.09	1.63	46.87	2.38	.51	.....	2.09	.21	34.18	100.00
Sodium sulphate—Magnesium chloride (Na ₂ SO ₄ —MgCl ₂).....	B	23.44	9.22	1.88	16.55	44.64	.28	2.41	1.50	.46	100.54	.....
Sodium sulphate—Magnesium sulphate (Na ₂ SO ₄ —MgSO ₄).....	A	24.57	8.66	2.24	14.83	42.94	.60	3.35	1.01	.19	2.37	100.76
Sodium sulphate—Magnesium sulphate (Na ₂ SO ₄ —MgSO ₄).....	B	25.67	10.10	2.06	7.12	46.17	4.26	2.02	2.35	.50	1.18	100.46
Sodium sulphate—Magnesium sulphate (Na ₂ SO ₄ —MgSO ₄).....	A	24.28	7.84	2.63	7.94	46.41	4.55	2.35	1.76	.13	2.63	100.52
Sodium sulphate—Magnesium sulphate (Na ₂ SO ₄ —MgSO ₄).....	B	8.64	5.20	1.23	44.96	1.96	.20	.....	2.25	.30	35.28	100.00
Sodium carbonate (Na ₂ CO ₃).....	A	9.07	4.48	1.57	45.93	2.28	.05	.....	2.06	.20	34.36	100.00
Calcium chloride (CaCl ₂).....	B	27.22	10.70	2.18	52.93	3.52	.33	.....	.61	.54	.19	100.51
Calcium chloride—Magnesium chloride (CaCl ₂ —MgCl ₂).....	A	27.75	10.33	2.23	47.49	3.94	.36	3.95	.08	.28	4.47	100.88
Calcium chloride—Magnesium chloride (CaCl ₂ —MgCl ₂).....	B	25.29	9.95	2.03	10.25	46.88	1.72	1.89	1.74	.50	.17	100.42
Magnesium chloride (MgCl ₂).....	A	25.32	7.99	2.18	12.43	43.19	2.47	3.29	.90	.20	2.76	100.73
Magnesium chloride (MgCl ₂).....	B	26.25	10.38	2.05	18.90	36.43	1.66	2.20	1.12	.51	1.18	100.50
Magnesium chloride—Magnesium sulphate (MgCl ₂ —MgSO ₄).....	A	24.24	8.78	2.05	19.90	37.32	1.90	3.33	1.93	.23	1.92	100.79
Magnesium chloride—Magnesium sulphate (MgCl ₂ —MgSO ₄).....	B	22.83	8.99	2.08	17.10	42.47	3.37	1.70	1.46	.45	1.16	100.38
Magnesium sulphate (MgSO ₄).....	A	26.53	8.86	2.06	15.62	42.88	2.66	1.34	1.13	Tr.	1.70	100.30
Magnesium sulphate (MgSO ₄).....	B	26.65	10.47	2.14	12.86	41.97	4.55	.06	.60	.52	1.19	100.01
Magnesium sulphate (MgSO ₄).....	A	24.60	8.79	2.32	13.44	43.71	5.16	.44	.47	.05	1.11	100.09

^a A, calculated from analyses of solution; B, analyses of final residue.

^b Residue lost by flask breaking.

TABLE 5

Comparison of Lime Removed from Unset and Set Cement by Various Solutions

Solution used	Unset cement		Set cement	
	Per cent of CaO removed	Period of exposure	Per cent CaO removed	Period of exposure
NaCl.....	50.7	Weeks 6	63.7	6
MgCl ₂		(a)	72.6	24
NaCl.....	73.8	26		
MgSO ₄	84.2	74	87.9	24
Na ₂ SO ₄	66.7	26		
MgCl ₂	76.3	70	91.7	24
Na ₂ SO ₄	34.4	12	41.3	11
MgSO ₄	90.7	74		(a)
Na ₂ CO ₃ ^b	91.1	12	66.6	12
	99.6	44		
CaCl ₂	70.5	26	74.1	24
MgCl ₂	86.4	78		
MgCl ₂	66.1	26	93.3	24
MgSO ₄	74.9	74		
	64.4	26	88.8	24
MgCl ₂	75.8	78		
	39.3	12	45.9	11
MgSO ₄	83.8	74		(a)

^a Discontinued.

^b Lime not removed but converted into calcium carbonate.

TABLE 6

Comparison of the Analyses of the Residues Obtained as a Result of the Action of Various Solutions Upon the Set Cement, With the Residues Calculated from the Changes in the Composition of the Solutions Observed After They Had Been Withdrawn from the Cement

Solution used	Method ^a	Percentages of components obtained by analyses—											
		SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₂	Cl	Na ₂ O	K ₂ O	CO ₂	Total	O for Cl
NaCl-MgCl ₂	A	22.59	8.30	2.09	18.35	37.42	4.21	3.25	1.70	0.43	2.39	100.73	6.73
	B	23.34	7.42	2.36	17.92	36.26	4.21	3.12	1.11	.17	4.80	100.71	.71
NaCl-MgSO ₄	A	19.81	7.27	1.83	7.08	41.03	15.84	2.76	2.54	.38	2.09	100.63	.63
	B	19.46	6.78	1.91	8.84	40.37	12.48	3.79	2.49	.17	4.57	100.86	.86
Na ₂ SO ₄ -MgCl ₂	A	21.73	7.98	2.00	5.33	48.38	7.88	2.43	2.10	.42	2.29	100.54	.54
	B	23.23	8.19	2.34	4.88	47.28	5.28	4.10	1.80	.10	3.67	100.87	.87
Na ₂ SO ₄ -MgSO ₄	A	11.14	4.10	1.03	19.82	25.69	34.87	.....	1.97	.21	1.17	100.00	....
	B	11.55	3.88	1.32	20.61	25.23	32.46	.....	1.52	.05	3.38	100.00	....
	A	9.77	4.08	1.35	43.44	1.80	.17	.....	2.90	.28	36.22	100.01	.01
Na ₂ CO ₃	B	10.70	4.27	1.74	45.57	2.29	.17	.....	2.91	.09	32.26	100.00	....
	A	22.10	8.12	2.04	16.95	38.59	5.29	2.94	1.89	.42	2.32	100.66	.66
CaCl ₂ -MgCl ₂	B	21.35	7.71	2.41	16.29	38.00	4.33	3.91	1.39	.14	5.35	100.88	.88
	A	22.73	8.35	2.09	4.49	52.41	5.83	.99	.50	.44	2.39	100.22	.22
MgCl ₂ -MgSO ₄	B	23.76	8.84	2.06	5.98	48.71	4.33	1.94	.30	.18	4.34	100.44	.44
	A	21.53	7.91	1.98	7.14	53.41	2.75	1.72	1.27	.41	2.77	100.39	.39
MgCl ₂	B	22.50	8.36	1.96	8.81	48.13	2.82	2.46	.84	.16	4.52	100.56	.56
	A	12.02	4.42	1.10	19.61	29.84	31.26	.....	.26	.23	1.26	100.00	....
MgSO ₄	B	13.06	4.34	1.35	21.92	27.87	28.85	.....	.08	.03	2.50	100.00	....

^a A, Calculated from analyses of solution; B, analyses of final residue.

TABLE 7

Comparison of the Residues Obtained as the Result of the Action of Distilled Water upon Various Cements, with the Residue Calculated from Material Dissolved by the Distilled Water Observed when the Latter was Removed from the Cement

	24-1 unset				24-1 set				47 unset				47 set			
	Original	Calculated	Analysed	Analysed CO ₂ reduced ^d	Original	Calculated	Analysed	Analysed CO ₂ reduced	Original	Calculated	Analysed	Analysed CO ₂ reduced	Original	Calculated	Analysed	Analysed CO ₂ reduced
SiO ₂	30.19	35.00	34.97	35.63	26.31	31.51	31.19	30.77	21.03	31.60	31.74	32.60	17.73	23.75	24.55	24.47
Al ₂ O ₃	11.08	12.85	12.11	12.34	10.18	12.20	11.09	10.92	7.13	10.70	11.06	11.36	5.99	8.04	9.22	9.19
Fe ₂ O ₃	1.64	1.90	1.83	1.86	1.46	1.75	2.60	2.54	2.30	3.45	2.64	2.71	2.09	2.79	1.94	1.93
CaO.....	46.16	41.62	42.48	43.29	40.08	38.42	40.69	40.15	61.62	46.92	43.26	44.43	52.10	48.77	47.77	47.62
MgO.....	2.17	2.50	1.55	1.58	1.72	2.06	2.32	2.27	3.16	3.24	4.38	4.70	2.72	3.65	3.98	3.97
SO ₃	1.10	1.27	1.56	1.59	1.24	1.49	.80	.78	1.44	2.16	1.98	2.03	1.21	1.61	1.46	1.45
Na ₂ O.....	.29	.32	.32	.32	.30	.36	.47	.45	.11	.16	.55	.56	.11	.13	.42	.41
K ₂ O.....	.64	.75	.56	.57	.64	.77	.32	.30	.32	.48	.31	.32	.41	.59	.30	.29
CaS.....	2.74	2.95	1.94	1.98	2.09	1.10	1.52	1.48	.87	1.29	3.88	1.29	7.96	10.67	10.36	10.67
CO ₂.....	.72	.84	2.68	.64	8.64	10.34	9.00	10.34	1.83	1.29	100.00	100.00	9.54	100.00	100.00	100.00
Total.....	100.01	100.00	100.00	100.00	100.12	100.00	100.00	100.00	99.81	100.00	100.00	100.00	99.86	100.00	100.00	100.00

^a Analysis of original cement.

^b Residue "calculated" from material dissolved by the water, as determined by periodical analyses.

^c Residue "analyzed" at end of the tests.

^d "Analysed CO₂ reduced" residue obtained by reducing the analyzed residue to a CO₂ basis equivalent to the calculated residue.

TABLE 7—Continued

	52 unset				52 set				53 unset				53 set			
	Original	Calculated	Analyzed	Analyzed CO ₂ reduced	Original	Calculated	Analyzed	Analyzed CO ₂ reduced	Original	Calculated	Analyzed	Analyzed CO ₂ reduced	Original	Calculated	Analyzed	Analyzed CO ₂ reduced
SiO ₂	24.53	29.33	28.09	29.42	22.43	25.05	23.52	24.47	23.04	32.65	33.31	34.39	20.43	25.29	24.68	24.56
Al ₂ O ₃	6.98	10.74	10.03	10.50	6.35	7.34	6.40	6.78	7.18	10.19	10.29	10.62	5.46	8.00	7.96	7.82
Fe ₂ O ₃	45.75	36.04	37.43	36.27	47.36	46.85	46.00	41.54	51.51	49.55	46.00	46.11	56.17	53.10	54.27	54.00
CaO.....	2.02	2.19	3.56	3.73	2.70	3.02	2.27	3.11	1.04	1.47	2.15	2.23	1.01	1.24	1.39	1.36
MgO.....	1.81	2.15	1.73	1.81	1.68	1.87	1.27	1.32	.43	.39	.54	.56	.39	.50	.47	.47
SO ₃	1.39	1.43	.21	.53	1.29	1.31	.41	.43	.23	.34	.13	.13	.22	.15	.21	.21
FeO.....	1.20	1.43	.68	.71	1.10	1.23	.76	.79	.63	.86	.14	.14	.50	.62	.41	.41
CO ₂	8.60	10.30	14.35	10.30	14.19	15.85	19.13	15.85	.27	.37	3.50	.37	6.61	8.17	7.72	8.17
Loss.....	5.53				6.05				1.17				6.15			
Total.....	100.16	100.00	100.00	100.00	100.38	100.00	100.00	100.00	100.10	100.00	100.00	100.00	100.15	100.00	100.00	100.00

TABLE 8

Comparison of the Residue Obtained as the Result of the Action of Sea Water upon Various Cements, with the Residue Calculated from the Changes in Composition Observed in the Sea Water when Removed from the Cements

Cement ^a		SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CuO	CaO	MgO	SO ₂	Cl	Na ₂ O	K ₂ O	CO ₂	CaS	H ₂ O	Ig	Total	O for Cl	Sea salts in residue		
																		MgO	Na ₂ O	SO ₂
4.....	Original ^b	23.44	2.98	7.48	0.51	61.86	0.50	1.72	.....	0.20	0.28	0.69	.....	0.42	0.09	100.17	.....	.....	.....	.....
	Calculated	27.92	3.59	9.02	.62	11.16	44.10	2.07	.....	.24	.34	.94	.....	.....	.....	100.00	.....	.....	.....	.....
	Analyzed ^c	25.68	2.36	8.83	.54	13.71	35.65	1.34	3.60	2.11	.49	6.50	.....	.....	.....	100.80	0.80	.....	.....	.....
	Analyzed CO ₂ reduced ^d	27.22	2.50	9.34	.58	14.52	37.77	1.42	3.81	2.23	.52	.94	.....	.....	.....	100.85	.85	.....	.....	.....
5.....	Original	21.08	7.73	2.34	.....	63.38	2.37	1.48	.....	.42	.57	.41	.....	.....	.06	99.84	.....	.....	.....	.....
	Calculated	25.27	9.27	2.81	.....	12.91	46.23	1.77	.....	.50	.68	.56	.....	.....	.....	100.00	.....	.....	.....	.....
	Analyzed	22.81	8.59	2.78	.....	11.03	37.87	2.44	5.56	2.67	.40	7.11	.....	.....	.....	101.26	1.26	.....	.....	.....
	Analyzed CO ₂ reduced	24.42	9.20	2.98	.....	11.81	40.53	2.61	5.95	2.86	.43	.56	.....	.....	.....	101.35	1.35	.....	.....	.....
23.....	Original	21.45	8.44	1.72	.....	63.85	2.77	.26	.....	.48	.42	.15	.....	.08	.55	100.17	.....	.....	.....	.....
	Calculated	25.75	10.13	2.06	.....	14.07	45.76	.31	.....	.58	.50	.84	.....	.....	.....	100.00	.....	.....	.....	.....
	Analyzed	23.59	9.16	2.61	.....	12.29	37.28	2.53	4.59	2.11	.43	6.45	.....	.....	.....	101.03	1.03	.....	.....	.....
	Analyzed CO ₂ reduced	25.00	9.70	2.77	.....	13.02	39.51	2.68	4.87	2.24	.46	.84	.....	.....	.....	101.09	1.09	.....	.....	.....
24A.....	Original	30.03	10.60	.95	.....	46.75	5.32	.80	.....	.24	.58	.84	2.08	.....	2.94	100.29	.....	.....	.....	.....
	Calculated	30.19	11.08	1.64	.....	46.16	2.17	1.10	.....	.29	.64	.72	2.74	.....	3.28	100.01	.....	.....	.....	.....
	Analyzed	28.87	10.60	1.57	.....	25.14	18.98	.61	7.56	2.75	.61	.69	2.62	.....	.....	100.00	.....	.....	.....	.....
	Analyzed CO ₂ reduced	29.09	10.83	1.46	.....	23.79	18.27	1.43	2.99	2.76	.67	7.23	2.15	.....	.....	100.67	.67	0.33	2.34	0.33
24-1.....	Original	31.14	11.59	1.56	.....	25.48	19.56	1.53	3.20	2.95	.72	.69	2.30	.....	.....	100.72	.72	.....	.....	.....
	Calculated	26.31	10.18	1.46	.....	40.08	1.72	1.24	.....	.30	.64	8.64	2.09	.....	7.46	100.12	.....	.....	.....	.....
	Analyzed	28.02	10.84	1.55	.....	38.42	4.62	.89	2.11	1.45	.68	9.20	2.22	.....	.....	100.00	.....	.....	.....	.....
	Analyzed CO ₂ reduced	27.09	10.39	1.66	.....	36.68	4.91	1.43	1.77	1.48	.81	12.91	1.27	.....	.....	100.40	.40	.18	1.10	.16
24-1 set.....	Original	28.25	10.83	1.73	.....	38.25	5.12	1.49	1.85	1.54	.84	9.20	1.32	.....	.....	100.42	.42	.....	.....	.....
	Calculated	25.80	6.84	4.60	.....	33.51	20.98	1.10	.....	.49	1.42	5.11	.....	.....	.39	100.24	.....	.....	.....	.....
	Analyzed	26.10	6.90	4.64	.....	14.66	39.13	1.11	.....	.49	1.43	5.54	.....	.....	.....	100.00	.....	.....	.....	.....
	Analyzed CO ₂ reduced	24.51	7.10	4.55	.....	13.27	34.18	1.16	4.53	2.14	1.28	8.30	.....	.....	.....	101.02	1.02	.....	.....	.....
25.....	Original	25.25	7.31	4.69	.....	13.68	35.20	1.19	4.67	2.20	1.32	5.54	.....	.....	.....	101.05	1.05	.....	.....	.....
	Calculated	25.25	7.31	4.69	.....	13.68	35.20	1.19	4.67	2.20	1.32	5.54	.....	.....	.....	101.05	1.05	.....	.....	.....

^a Unless otherwise noted, the cements used were unset.

^b Analyses of original cement.

^c "Calculated dry residue," made from periodical analyses of the water removed.

^d "Analyzed dry residue," is analysis of dry residue at the end of the tests, includes sea salts gained by drying the wet residue.

^e "Analyzed CO₂ reduced dry residue" obtained by reducing the "analyzed dry residue" to a CO₂ basis equivalent to the "calculated dry residue."

^f Not determined.

^g No residue received.

TABLE 8—Continued

Cement a	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CuO	CaO	MgO	SO ₃	Cl	Na ₂ O	K ₂ O	CO ₂	CaS	H ₂ O	I ₂	Total	O for Cl	Sea salts in residue			
																	MgO	Na ₂ O	SO ₃	Cl
30.	Original.....	22.66	8.61	0.55	.....	.....	.....	.....	.....	.....	0.63	.....	0.36	1.07	100.01	.....	.....	.....	.....
	Calculated.....	25.21	9.58	.61	.....	23.36	1.80	4.01	.98	.59	.70	.....	.....	.....	100.00	.....	.....	.....	.....
	Analyzed.....	25.81	8.89	.69	.....	23.63	28.99	2.24	1.53	.48	6.95	.....	.....	.....	100.49	0.49	0.11	0.75	0.12
	Analyzed CO ₂ reduced.....	27.54	9.49	.74	.....	25.22	30.94	1.37	2.39	1.63	.51	.70	.....	.....	100.53	.53	.....	.....	.....
47.	Original.....	23.38	7.92	2.56	.....	16.80	42.47	3.31	1.02	.36	.96	.....	.....	.....	100.00	.....	.....	.....	.....
	Calculated.....	22.21	7.68	2.19	.....	15.34	35.49	1.59	3.67	1.98	.37	.....	.....	.....	100.82	.82	.23	1.56	.24
	Analyzed.....	24.52	8.48	2.42	.....	16.84	39.10	1.76	4.05	2.19	.48	.....	.....	.....	100.90	.90	.....	.....	.....
	Analyzed CO ₂ reduced.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
47 set.	Original.....	17.73	5.99	2.09	.....	52.10	2.72	1.21	.....	.41	7.96	.....	.....	9.54	99.86	.....	.....	.....	.....
	Calculated.....	20.50	6.92	2.40	.....	24.10	29.83	1.71	4.27	1.13	.94	.....	.....	.....	100.00	.....	.....	.....	.....
	Analyzed.....	20.13	6.64	1.46	.....	23.57	28.44	1.25	2.21	1.51	.35	.....	.....	.....	100.49	.49	.12	.83	.12
	Analyzed CO ₂ reduced.....	21.49	7.09	1.55	.....	25.17	30.35	1.33	2.36	1.61	.37	9.20	.....	.....	100.52	.52	.....	.....	.....
52.	Original.....	24.53	8.98	2.45	.....	45.75	2.92	1.81	.39	1.20	8.60	.....	.....	3.53	100.16	.....	.....	.....	.....
	Calculated.....	25.20	9.23	2.51	.....	22.32	21.44	.99	6.41	1.83	1.23	.....	.....	.....	100.00	.....	.....	.....	.....
	Analyzed.....	24.99	9.25	2.05	.....	21.78	20.81	1.39	3.07	1.96	1.06	0.16	.....	.....	100.69	.69	.20	1.34	.21
	Analyzed CO ₂ reduced.....	26.53	9.82	2.18	.....	23.13	22.11	1.48	3.26	2.08	1.13	8.84	.17	.....	100.73	.73	.....	.....	.....
52 set.	Original.....	22.43	8.35	2.23	.....	41.36	2.70	1.68	.29	1.10	14.19	.....	.....	6.05	100.38	.....	.....	.....	.....
	Calculated.....	23.77	8.85	2.35	.....	25.82	16.57	1.35	3.69	1.38	1.17	.....	.....	.....	100.00	.....	.....	.....	.....
	Analyzed.....	24.41	9.70	2.10	.....	25.67	14.65	1.30	1.71	1.44	.89	.12	.....	.....	100.80	.30	.14	1.04	.15
	Analyzed CO ₂ reduced.....	25.39	10.09	2.18	.....	26.69	15.24	1.35	1.78	1.50	.92	15.05	.12	.....	100.31	.31	.....	.....	.....
53.	Original.....	25.19	7.85	2.73	.....	21.03	36.12	.96	3.21	.68	.28	.....	.....	.....	100.00	.....	.....	.....	.....
	Calculated.....	23.96	7.55	2.19	.....	19.92	33.76	1.25	3.89	2.36	.47	.....	.....	.....	100.88	.88	.26	1.74	.26
	Analyzed.....	25.29	7.97	2.31	.....	21.03	35.64	1.32	4.11	2.49	.49	.....	.....	.....	100.93	.93	.....	.....	.....
	Analyzed CO ₂ reduced.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
53 set.	Original.....	20.43	6.46	2.31	.....	56.17	1.01	.39	.12	.50	6.61	.....	.....	6.15	100.15	.....	.....	.....	.....
	Calculated.....	23.03	7.29	2.62	.....	27.86	26.53	.95	2.68	1.04	.56	.....	.....	.....	100.00	.....	.....	.....	.....
	Analyzed.....	22.92	7.06	2.35	.....	27.23	25.07	.94	1.91	.72	.26	.....	.....	.....	100.43	.43	.11	.79	.11
	Analyzed CO ₂ reduced.....	24.10	7.42	2.47	.....	28.63	26.36	.99	2.01	.76	.27	7.44	.....	.....	100.45	.45	.....	.....	.....

TABLE 9
Chemical Analyses of Various Cements, Limes, Plaster, and Sand

Cement or materials	Material No.	Percentage of various constituents										Ignition loss	Total
		Silica (SiO ₂)	Alumina (Al ₂ O ₃)	Ferric oxide (Fe ₂ O ₃)	Lime (CaO)	Magnesia (MgO)	Sulphuric anhydride (SO ₃)	Soda (Na ₂ O)	Potash (K ₂ O)	Carbon dioxide (CO ₂)	Calcium sulphide (CaS)	Water (H ₂ O)	
Typical sea water...	...	0.001	0.0011	0.054	0.193	0.190	1.32	0.005	(Chlorine = 1.71)	96.526	...	...	...
Deionized lime...	3	0.95	0.41	0.44	45.49	32.36	0.41	0.25	0.20	5.04	...	14.50	100.16
High calcium lime...	3b	1.13	0.36	0.44	70.90	1.13	1.72	0.20	0.28	0.69	...	0.11	100.80
German Portland cement ^a ...	4	23.44	7.76	7.48	61.86	0.50	1.48	0.42	0.57	0.41	...	0.42	100.17
Portland cement (American)...	5	21.08	8.44	1.72	63.38	2.37	1.26	0.48	0.42	0.15	...	0.07	99.85
Portland cement, special (American)...	23	21.45	8.44	1.01	63.85	5.17	0.80	0.47	0.55	0.84	...	0.08	100.17
Slag cement...	24	29.88	11.07	1.64	45.75	2.17	1.10	0.29	0.64	0.72	1.82	0.11	100.15
Slag cement (second sample)...	24b	30.19	11.08	1.64	46.16	33.51	1.10	0.49	1.42	5.11	2.74	...	100.01
Natural cement...	25	25.80	11.44	4.60	32.96	16.38	2.15	0.51	2.53	10.17	...	0.39	100.24
Do.	26	20.90	6.02	2.44	32.96	21.21	1.86	0.37	1.17	4.56	...	0.27	100.11
Do.	27	22.38	7.17	2.01	48.01	12.16	1.76	0.59	1.18	10.02	...	0.30	100.27
Do.	28	22.32	9.44	2.74	46.06	2.61	1.76	0.24	0.51	0.04	...	0.87	100.24
Portland cement (American)...	29	19.45	7.61	6.89	63.06	0.88	1.39	0.24	0.53	0.63	...	0.16	100.26
Non-setting cement...	30	22.66	8.61	0.55	62.46	1.10	1.64	0.40	0.72	1.01	...	0.36	100.01
Portland cement (American)...	31	20.09	7.51	2.70	62.09	2.78	1.46	0.47	0.72	0.43	...	0.50	100.16
Blended cement...	32	24.00	9.69	2.53	49.15	2.53	1.67	0.71	1.42	5.65	...	0.45	100.05
Natural cement...	33	24.02	10.42	2.61	46.66	2.63	1.63	0.80	1.66	0.78	...	0.70	100.11
Portland cement (American)...	34	21.36	6.77	3.73	63.43	1.59	1.41	0.09	0.31	0.73	...	0.43	100.26
Do.	35	20.26	7.25	2.66	63.17	1.24	1.75	0.40	0.68	0.70	...	0.70	100.23
Do.	36	21.29	6.28	2.80	62.34	3.50	1.46	0.16	0.28	0.52	...	0.39	100.32
Do.	37	21.03	7.70	2.70	61.78	3.04	1.59	0.26	0.56	0.78	...	0.21	100.11
Do.	38	22.04	7.28	2.57	61.59	3.17	1.47	0.40	0.32	0.86	...	0.37	100.26
Do.	39	19.82	7.62	2.10	62.04	3.90	1.43	0.24	0.26	0.92	...	0.90	100.13
Do.	40	20.47	8.18	2.66	62.41	3.06	1.58	0.16	0.54	0.20	...	0.33	100.35
Do.	41	22.98	6.07	2.19	63.49	3.54	1.94	0.03	0.20	0.15	...	0.15	100.35
Do.	42	20.28	7.57	2.61	62.93	2.82	1.68	0.30	0.68	0.30	...	0.19	100.16
Do.	43	22.07	6.95	2.31	62.33	2.76	1.54	0.31	0.57	0.45	...	0.45	100.16
Do.	44	20.27	7.55	2.55	62.28	2.76	1.51	0.41	0.75	1.08	...	0.47	100.12
Do.	45	21.69	6.67	2.40	62.02	3.44	1.45	0.44	0.80	0.22	...	0.60	100.16
Do.	46	20.95	7.79	2.40	60.48	3.28	1.76	0.16	0.90	1.11	...	0.53	100.16
Do.	47	21.50	8.12	2.28	62.23	3.24	1.45	0.18	0.38	0.12	...	0.38	100.27
Typical Portland cement (American) ^b ...	48	22.48	6.52	3.64	62.03	0.66	1.56	0.29	0.52	0.95	...	0.73	100.12

^a Cement No. 4 contains 0.51 per cent of copper oxide (CuO).

^b Cement No. 47 is a typical Portland cement, mixture of cements Nos. 36 to 46, inclusive.

TABLE 9—Continued

Cement or materials	Material No.	Percentage of various constituents												
		Silica (SiO ₂)	Alumina (Al ₂ O ₃)	Ferric oxide (Fe ₂ O ₃)	Lime (CaO)	Magnesia (MgO)	Sulphuric anhydride (SO ₃)	Soda (Na ₂ O)	Potasses (K ₂ O)	Carbon dioxide (CO ₂)	Calcium sulphide (CaS)	Water (H ₂ O)	Ignition loss	Total
Sand a.....	51	93.91	2.08	1.93	0.26	Trace	Trace	0.13	0.56	0.14	.....	0.27	0.50	100.11
Natural cement.....	52	22.53	8.98	2.45	45.75	2.92	1.81	0.39	1.20	8.60	.....	.....	3.53	100.16
French Portland cement.....	53	23.04	7.18	2.51	63.60	1.04	0.43	0.23	0.63	0.27	.....	.....	1.17	100.10
Typical Portland cement (American) b.....	54	23.09	6.51	2.69	61.79	2.82	1.27	0.21	0.36	0.53	.....	.....	0.95	100.22
Do.....	54b	21.60	6.92	2.51	62.14	2.70	1.28	0.35	0.68	0.37	.....	.....	1.72	100.27
Special Portland cement (American).....	55	20.37	3.64	3.97	61.42	0.82	1.19	1.54	0.24	1.01	.....	.....	1.06	100.26
Portland cement (American).....	56	22.25	6.63	2.26	63.84	2.41	1.07	0.21	0.32	0.66	.....	.....	0.48	100.13
Special slag cement.....	57	27.77	13.87	0.60	44.09	4.49	1.22	0.42	0.11	2.10	.....	.....	2.68	100.19
Do.....	57b	25.48	15.37	0.64	42.23	4.45	1.83	0.56	0.57	0.64	.....	.....	2.16	100.18
Portland cement (American).....	58	22.66	5.58	4.51	62.22	0.62	1.05	0.17	0.19	0.88	.....	.....	1.98	99.86
Plaster of Paris.....	59	0.48	10.69	0.14	38.27	.....	52.98	.....	.....	.....	8.26	.....	.....	100.05
Natural cement.....	59	23.44	3.83	6.05	44.80	3.44	2.04	1.19	0.83	5.34	0.28	.....	5.83	100.29
Portland cement (American).....	60	24.02	.....	.....	61.93	0.69	1.50	0.68	0.44	0.37	.....	.....	0.75	100.26

^a Sand 52 also contains ferrous sulphide, 0.23; manganese oxide, 0.03; phosphorous pentoxide, 0.05; and chlorine (Cl), 0.02.

^b Cement No. 54 is a typical Portland cement, mixture of cements Nos. 36 to 41, inclusive.

NOTE.—The above analyses comprise the following brands of materials: Charles Warner's hydrated lime, Hemmner special cement fabriek, Yankton Portland cement, Dragon Portland cement, Vulcanite Portland cement, Ashgrove Portland cement, Allen American Portland cement, Lehigh Portland cement, Pennsylvania Portland cement, Giant Portland cement, Edison Portland cement, Atlas Portland cement, Saylor's Portland cement, Alpha Portland cement, Whitehall Portland cement, Phoenix Portland cement, Dexter Portland cement, Superior Portland cement, Allentown Portland cement, Jamestown Portland cement, Marine Portland cement, Struthers slag cement, Collos slag cement, Brooklyn Bridge-Rosedale natural cement, Improved Utica hydraulic cement, Star Brand natural cement, Union natural cement, improved Shield cement, Shield hydraulic cement, Union natural cement, Boulogne-sur-mer cement, mixture of Alca and Union natural and Blanc stainless cement.

TABLE 10

Physical Properties of Various Cements

Cement	Cement No.	Specific gravity	Fineness, per cent retained on—		Normal consistency, per cent of water used	Time of set	
			Sieve No. 100	Sieve No. 200		Initial	Final
German Portland cement.....	4	3.272	3.9	21.5	20.0	h m	h m
Portland cement (American).....	5	3.140	5.8	24.5	20.0	23 30	72 0
Portland cement (special).....	23	3.165	5.7	21.9	23.0	3 35	7 55
Slag cement.....	24	2.907	.3	2.9	31.0	4 10	8 10
Do.....	24b	2.815	.3	4.4	.....	8 15	18 0
Natural cement.....	25	3.012	4.9	23.5	38.0	7 10	31 30
Do.....	26	2.920	9.3	23.6	38.0	5 0	10 5
Do.....	26b	2.895	12.7	24.4	35.0	2 30	7 15
Do.....	27	3.040	4.8	11.9	36.0	1 0	2 25
Do.....	28	2.825	2.1	9.9	35.0	1 0	4 22
Portland cement (American).....	29	3.180	1.6	14.4	25.0	2 10	4 50
Nonstaining.....	30	3.110	3.3	21.5	23.5	8 18	12 50
Do.....	30b	3.115	3.9	21.9	22.0	0 45	6 5
Portland cement (American).....	31	.....	4.7	22.6	23.1	1 20	5 40
Blended cement.....	32	2.925	3.9	13.8	26.9	.....	.....
Natural cement.....	33	2.900	2.9	14.3	27.7	.....	.....
Portland cement (American).....	34	3.155	2.7	14.9	24.5	5 0	12 21
Do.....	35	3.094	2.4	15.1	26.9	.....	.....
Do.....	36	3.100	3.4	15.7	23.5	5 20	11 10
Do.....	37	3.100	4.6	21.7	22.5	4 47	9 5
Do.....	38	3.135	6.0	23.5	23.0	5 15	9 49
Do.....	39	3.069	4.6	19.3	27.0	5 22	9 13
Do.....	40	3.109	4.5	21.9	22.0	3 55	6 25
Do.....	41	3.145	3.9	21.5	22.5	5 23	10 7
Do.....	42	3.100	5.7	26.0	21.5	5 16	8 26
Do.....	43	3.110	6.6	23.1	23.0	4 57	6 12
Do.....	44	3.095	3.8	20.1	22.0	4 45	8 20
Do.....	45	3.105	3.5	17.6	24.0	4 45	7 45
Do.....	46	3.048	4.0	21.7	22.5	3 55	7 45
Typical Portland cement (American) ^a	47	3.134	5.1	21.1	21.2	3 55	7 40
Portland cement (American).....	48	3.107	3.4	16.1	26.0	9 2	16 0
Do.....	48b	3.137	2.5	16.2	24.0	8 40	16 0
Natural cement.....	52	.....	3.4	7.6	.....	7 30	.....
Do.....	52b	2.847	4.4	12.0	.....	0 23	0 41
French cement.....	53	3.151	21.3	38.8	22.0	5 11	10 11
Typical Portland cement (American) ^b	54	3.160	5.3	20.5	22.0	5 20	10 0
Do.....	54b	3.134	8.0	21.5	22.5	5 20	9 58
Portland cement (special).....	55	3.230	4.1	12.2	23.0	7 53	14 18
Portland cement (American).....	56	3.122	3.8	13.9	22.5	5 17	8 2
Special slag cement.....	57	2.847	2.0	3.5	29.0	10 15	20 0
Do.....	57b	2.912	1.0	2.7	25.5	6 30	14 0
Portland cement (American).....	58	3.155	3.1	17.3	22.0	5 5	8 45
Natural cement.....	59	2.869	3.3	17.0	30.5	2 40	5 20

^a Typical Portland cement No. 47 is a mixture of cements Nos. 36 to 46, inclusive.^b Typical Portland cement Nos. 54 and 54b are a mixture of cements Nos. 36 to 47, inclusive.

TABLE 11
Compressive Strength of 1:2:4 Portland Cement Concrete Stored in Sea Water
1 PART TYPICAL PORTLAND CEMENT NO. 47, 2 PARTS JERSEY SAND, 4 PARTS TRAP ROCK

Method of placing concrete in sea water	Age when tested, in weeks	Period of exposure	Test piece number	Weight in pounds per cubic foot	Compressive strength, pounds per square inch			Character of failure	Remarks
					Average	Maxi- mum	Mini- mum		
Deposited through a 5-inch tremie.	4	8/5/09- 9/20/09	136-138	158.6	608	641	580	.....	The cement is soft and "chalky," and can easily be rubbed from stones.
Do.....	13	8/20/09-11/19/09	139-141	155.5	662	719	594	A, A, A	The cement is soft and "chalky," and can be easily rubbed from stones. One corner of test piece No. 140 was slightly damaged before testing.
Do.....	26	8/25/09- 2/23/10	148-150	158.3	965	1114	823	B, B, B	The cement is soft and "chalky." In test piece No. 150, a white deposit was found to a depth of 1 1/2 inches from the surface, and crystals were observed throughout the interior of the core of this test piece.
Do.....	52	8/30/09- 8/30/10	163-165	155.3	1169	1309	1022	A, A, A	The deposit was found all three test pieces No. 165 and to a depth of 3 inches in test pieces Nos. 163-164. Crystals were observed through the interior of all test pieces in large quantities.
Do.....	104	9/3/09- 9/3/11	172-174	157.2	997	1165	853	A, A, A	Test pieces completely saturated with water. White deposit and crystals found all through. The surfaces were rough and worn away in places to a depth of one-half inch to 1 inch.
Do.....	182	9/14/09- 3/-/13	187-189	.....	1119	1221	1034	A, C, B	The surfaces were rough, but concrete appeared hard and sound. Crystals and white deposit in interior. A few stones were sheared.
Immersed immediately after depositing in molds.	4	7/16/09- 8/13/09	112-114	156.7	2175	2270	2009	.....	The concrete appeared normal.
Do.....	13	11/2/09- 2/1/10	223-225	156.6	2129	2288	1955	A, A, A	Do.
Do.....	26	7/1/09-12/30/09	106-108	159.7	3978+	3978+	3678+	A, A, A	None of these test pieces failed under a load of 200 000 pounds, the capacity of the testing machine. The concrete appeared normal.
Do.....	52	6/22/09- 6/22/10	58- 60	156.3	3630	3781	3511	A, C, A	The surfaces of test pieces appear to be slightly "bilistered." The center core of each test piece 3 inches diameter by 8 inches long appears dry. Concrete appears normal, excepting the "bilisters." About 50 per cent of stones in fractures were sheared.

Stored in damp room 24 hours before immersing.	4	10/28/09-11/24/09	205-207	155.4	1953	2071	1876	A, A, A	The concrete appears to be normal. No stones in fractures were sheared.
Do.....	13	11/6/09- 2/4/10	226-228	156.7	2727	3163	2507	A, C, A	The concrete appears normal. No stones in fractures appear to be sheared.
Do.....	26	12/1/09- 5/30/10	247-249	155.5	2797	2947	2591	D, A, A	In test piece No. 247 water penetrated to a depth of 2 inches from surface. White deposit was observed to a depth of three-fourths inch. In test piece No. 248 water penetrated completely; white deposit was observed to depth of 2 inches. In test piece No. 249 water penetrated completely, but no white deposit was observed. In all test pieces no stones in fractures were sheared. The concrete appears normal. No stones were sheared.
Stored in damp room 3 days before immersing.	4	10/30/09-11/24/09	208-210	154.5	1948	1989	1903	A, A, A	Do.
Do.....	13	11/8/09- 2/4/10	229-231	154.8	2776	2874	2672	D, A, D	In test piece No. 250 water penetrated to a depth of 2 inches from surface. White deposit observed to a depth of one-fourth inch. In test piece No. 251 water penetrated to a depth of 2 inches. No white deposit noted. In test piece No. 252 water penetrated completely. No white deposit observed. Only a few stones were sheared in fracture of No. 250.
Do.....	26	12/3/09- 5/31/10	250-252	154.7	2984	3016	2963	A, A, A	The concrete appears normal. No stones in fractures were sheared.
Stored in damp room 7 days before immersing.	4	11/3/09-11/24/09	211-213	154.7	1957	1991	1934	A, A, A	Do.
Do.....	13	11/12/09- 2/4/10	232-234	157.2	2848	2944	2789	A, D, A	Water penetrated all test pieces to a depth of about 2 inches from the surface. No white deposit was observed in the concrete, and only a few stones were sheared in the fracture of test piece No. 253.
Do.....	26	12/7/09- 5/31/10	235-235	155.5	2762	2930	2550	D, B, A	The concrete appears normal. No stones were sheared.
Stored in damp room 4 weeks before immersing.	13	7/20/09- 9/21/09	61- 63	154.9	3830	3978	3715	.....	None of these test pieces failed under a load of 200,000, the capacity of the testing machine. The concrete appears to be normal.
Do.....	26	7/20/09-12/21/09	64- 66	155.8	3978+	3978+	3978+	.....	Water penetrated to a depth of about 2½ inches from the cylindrical surfaces and 4 inches from end surfaces, except test piece No. 68, which was completely saturated. There were small "blisters" along the edges of test pieces. When removed from water the test pieces were covered with a 3-inch layer of shells and mussels. About 50 per cent of stones were sheared in fractures.
Do.....	52	7/20/09- 6/22/10	67- 69	154.6	3772	3817	3717	A, A, A	The concrete appears normal. No stones were sheared.
Stored in damp room 8 weeks before immersing.	13	8/14/09- 9/18/09	34- 36	156.3	3877	3958	3828	.....	Test piece No. 37 sheared about 50 per cent of the stones in the fracture. Test pieces No. 38 and No. 39 did not fail under a load of 200,000 pounds, the capacity of the testing machine. Concrete appears normal.
Do.....	26	8/14/09-12/18/09	37- 39	156.4	3979+	3982	3978+	A	Water penetrated to a depth of from 2 inches to 2½ inches from cylindrical surfaces and from 4 inches to ½ inches from end surfaces. Surfaces were rough and covered with small "blisters" which shelled off pieces one-sixteenth inch to one-eighth inch thick in places. All stones were sheared in fracture.
Do.....	52	8/14/09- 6/19/10	40- 42	156.5	4060	4086	4041	A, D, A	

TABLE 11—Continued

Method of placing concrete in sea water	Age when tested, in weeks	Period of exposure	Test piece number	Weight in pounds per cubic foot	Compressive strength, pounds per square inch			Character of failure	Remarks
					Average	Maxi- mum	Mini- mum		
Stored in damp room 8 weeks, then placed between tides.	13	8/26/09- 9/30/09	97- 99	158.	3959+	3978+	3921	Test piece No. 98 cracked vertically at one end. Test piece No. 99 did not fail under a load of 200 000 pounds, the capacity of the testing machine. Concrete appears normal. None of the test pieces failed under a load of 200 000 pounds the capacity of the testing machine. The concrete appears normal. An overload of 13 500 pounds in addition to the 200 000 pounds machine capacity was applied, but none of test pieces failed. The concrete appears normal. Practically all stones were sheared. The concrete appeared normal.
Do.....	26	8/16/09-12/20/09	52- 54	155. 7	3978+	3978+	3978+	.....
Do.....	52	8/26/09- 7/1/10	103-105	157. 5	4247+	4247+	4247+	.....
Do.....	177	12/23/09- 3/-/13	215-17-18	154. 6	4625	4874	4377	A, A, C	

TABLE 12
Compressive Strength of 1:2:4 Portland Cement Concrete Stored in Fresh Water
1 PART TYPICAL PORTLAND CEMENT NO. 47, 2 PARTS JERSEY SAND, 4 PARTS TRAP ROCK

Method of placing concrete in fresh water	Age when tested, in weeks	Period of exposure	Test piece number	Weight in pounds per cubic foot	Compressive strength, pounds per square inch			Character of failure	Remarks
					Average	Maximum	Minimum		
Deposited through a 5-inch tremie.	4	6/14/10- 7/12/10	281-283	152.8	1821	1863	1774	A, A, A	A few stones sheared.
Do.	13	6/14/10- 9/13/10	284-286	154.0	2156	2418	1912	A, A, B	A few stones sheared in test piece No. 285.
Do.	26	6/14/10-12/13/10	287-289	.....	2307	1835	2780	.....	Test piece No. 289 broken while digging from ice, therefore not included in results.
Do.	52	6/16/10- 6/16/11	291-293	157.6	2537	2689	2460	.....	All test pieces completely saturated. Test pieces Nos. 291 and 293 showed about 5 per cent sheared stone, and test piece No. 292 about 2 per cent. Concrete in all test pieces appeared firm and well set.
Immersed immediately after depositing in molds.	4	6/16/10- 7/14/10	294-296	158.9	2851	3024	2742	A, A, D	A few stones sheared in test piece No.296.
Do.	13	6/16/10- 9/15/10	297-299	158.7	3370+	3978+	2948	D, B, A	Test piece No. 298 cracked at lower end, but did not fail under a load of 200 000 pounds, the capacity of the machine. Test pieces Nos. 297 and 299 sheared about 50 per cent of stones. There is no apparent reason for this extreme variation.
Do.	26	6/16/10-12/15/10	300-302	158.0	4094+	4178+	3926	.....	Test piece No. 300 did not fail under a load of 210 000 pounds.
Do.	52	6/20/10- 6/20/11	303-305	157.9	3956	4083	3884	.....	All test pieces completely saturated and showed 5 per cent sheared stones. All test pieces broke with sudden failure.
Stored in damp room 24 hours before immersion.	4	6/19/09- 8/13/09	22-24	.....	3978+	3978+	3978	.....	Test pieces Nos. 22 and 24 failed while reversing machine. Test piece No. 23 did not fail under a load of 200 000 pounds, the capacity of the testing machine.
Do.	13	6/19/09- 9/17/09	25-27	156.7	3978+	3978+	3978+	.....	None of test pieces failed under a load of 200 000 pounds, the capacity of the testing machine.
Do.	26	6/19/09-12/17/09	28-30	158.2	4100+	4128+	4045	.....	Test pieces Nos. 28 and 29 failed when machine was overloaded to the load of 207 500, but test piece No. 30 did not fail under this load.
Do.	52	6/19/09- 6/18/10	31-33	154.2	4247+	4247+	4247+	.....	The machine was overloaded to a load of 213 500 pounds, but none of the test pieces failed.
Stored in damp room 8 weeks before immersion.	13	9/27/09-11/ 1/09	130-132	157.7	3190	3339	3045	A, A, A	A few stones were sheared.
Do.	26	9/27/09- 1/31/10	133-135	157.7	3457	3664	3339	A, A, A	Do.
Do.	52	10/25/09- 8/30/10	137-139	157.2	3369	3572	3062	A, A, D	Water penetrated the test pieces to a depth of about 3 inches from surfaces. About 50 per cent of stones were sheared.
Do.	104	10/25/09- 8/30/11	160-162	157.1	2758	3920	2167	B, C, C	A few stones were sheared.

^a Test piece No. 300 was retested 6/16/11 (one year) and failed under a load of 196 600 pounds.

TABLE 13
Compressive Strength of 1:3:6 Portland Cement Concrete Stored In Sea Water
1 PART TYPICAL PORTLAND CEMENT NO. 54, 3 PARTS JERSEY SAND, 6 PARTS TRAP ROCK

Method of placing concrete in sea water	Age when tested, in weeks	Period of exposure	Test piece number	Weight in pounds per cubic foot	Compressive strength, pounds per square inch			Character of failure	Remarks
					Average	Max- imum	Min- imum		
Deposited through a 5-inch tremie.	4	7/27/10- 8/24/10	393-395	153.5	512	636	404	D, B, B	All test pieces completely saturated. No stones sheared. In test piece No. 393 a white deposit was observed to a depth of one-half inch from surfaces, and crystals were noted throughout this test piece. In test piece No. 394 a white deposit was noted on surfaces and to a depth of one-fourth inch in from surfaces. In test piece No. 395 a white deposit was noted entirely through test piece. All surfaces of cylinder appeared perfect. Crystals were noted throughout all test pieces.
Do.....	13	8/ 1/10-10/31/10	396-398	154.0	552	616	478	A, A, A	All test pieces completely saturated and a large number of crystals observed throughout all test pieces. All test pieces showed a deposit of white material to a depth of 1 1/2 inches in from the surfaces.
Do.....	26	8/ 5/10- 2/ 3/11	405-407	153.8	533	569	512	D, A, A	All test pieces were completely saturated. About 3 per cent of the stones sheared. Very heavy deposits of crystals were noted. White deposit was found in all test pieces, especially in the end sections of the test pieces. Test piece No. 406 was found broken in the storage crate and was evened off to a length of 9 1/2 inches. Concrete was rather soft.
Do.....	52	8/ 9/10- 8/ 9/11	411-413	151.2	480	560	399	A, C, C	All test pieces completely saturated and heavy white deposit and crystals throughout. Test pieces were damaged. No. 413 so badly that its values are not included in the averages.
Stored in damp room 8 weeks before immersion.	13	8/17/10- 9/21/10	315-317	159.6	2242	2392	2197	A, A, D	All test pieces were completely saturated. Test piece No. 316 showed a spot of white deposit and a few crystals.
	26	8/17/10-12/21/10	318-320	156.3	2586	2715	2417	A, B, A	All test pieces were completely saturated. No stones sheared. Test pieces No. 318 and 319 showed a slight sheeling off of the surface.
Do.....	52	8/17/10- 6/22/11	321-323	158.2	2537	2789	2349	D, A, A	All test pieces were completely saturated. Test pieces Nos. 321 and 322 showed a few sheared stones.
Do.....	156	8/17/10- 2/ -/13	324-326	152.9	3026	3657	2622	D, B, B	About 25 per cent of stones were sheared.

1 PART TYPICAL PORTLAND CEMENT NO. 54, 3 PARTS JERSEY SAND, 6 PARTS GRAVEL

Stored in damp room 8 weeks before immersion.	13	8/22/10- 9/26/10	339-341	151.0	2089	2278	1928	D, A, D	All test pieces were completely saturated. Test piece No. 340 showed a white deposit $1\frac{1}{2}$ inches in from cylindrical surface and 3 inches in from end surface.
Do.....	26	8/22/10-12/26/10	342-344	148.5	2098	2163	1987	A, C, D	All test pieces were completely saturated. No stones were sheared and no white deposit.
Do.....	52	8/22/10- 6/27/11	345-347	148.8	2269	2325	2221	A, A, A	All test pieces saturated to a depth of 2 inches; interiors damp. No white deposit was observed.

TABLE 14
Compressive Strength of 1:3:6 Portland Cement Concrete Stored in Fresh Water
1 PART TYPICAL PORTLAND CEMENT NO. 54, 3 PARTS JERSEY SAND, 6 PARTS TRAP ROCK

Method of placing concrete in fresh water	Age when tested, in weeks	Period of exposure	Test piece number	Weight in pounds per cubic foot	Compressive strength, pounds per square inch			Character of failure	Remarks
					Average	Maximum	Minimum		
Deposited through a 5-inch tremie.	4	7/27/10- 8/24/10	390-392	157.2	499	512	395	B, B, B	All test pieces were completely saturated. No stones were sheared. Large number of crystals were observed throughout all the test pieces. The surfaces of test pieces appeared perfect.
Do.....	13	8/1/10-10/31/10	399-401	157.8	760	917	653	A, A, A	All test pieces were completely saturated. There were more crystals in these test pieces than in the corresponding sea-water test pieces. (The crystals appeared to be calcium carbonate.)
Do.....	26	8/5/10- 2/3/11	408-410	152.2	572	582	563	D, D, A	All test pieces were completely saturated. A few stones sheared, and all showed a great number of crystals around the stones. Test piece No. 409 cracked around the center, but the lower half of test piece did not fracture when tested. Test piece No. 410 was broken into two parts directly across the center. The concrete appeared firm.
Do.....	52	8/9/10- 8/9/11	414-416	151.0	702	780	546	A, A, A	All test pieces completely saturated, showing large quantity of crystals.
Stored in damp room 8 weeks before immersion.	13	11/17/10-12/22/10	420-422	157.9	1948	2097	1806	D, A, A	All test pieces were completely saturated and showed a small quantity of crystals to a depth of 1 inch in from surfaces. A few stones sheared.
Do.....	26	11/17/10- 3/23/11	423-425	158.7	2225	2367	2141	A, A, A	Test pieces Nos. 423 and 425 were saturated to a depth of 2 inches in from the surfaces. Interiors were damp. Test piece No. 424 was completely saturated. A few stones sheared in all test pieces.
Do.....	52	11/17/10- 9/12/11	426-428	158.5	2980	3350	2680	C, C	Test pieces saturated throughout, showing some sheared stones. There were a few crystals in the center of test pieces.

1 PART TYPICAL PORTLAND CEMENT NO. 54, 3 PARTS JERSEY SAND, 6 PARTS GRAVEL									
Stored in damp room 8 weeks before immersion.	13	8/19/10- 9/23/10	327-329	147.6	1816	1830	1803	A, A, C	All test pieces were completely saturated.
Do.....	26	8/19/10-12/23/10	330-332	148.0	2204	2237	2174	D, D, A	All test pieces were completely saturated. No stones were sheared.
Do.....	52	8/19/10- 6/24/11	333-335	149.0	2311	2440	2180	A, A, A	Do.
Do.....	136	8/19/10- 2/-/13	336-338	144.5	2792	2968	2499	A, A, C	No stones were sheared. Concrete appeared normal.

TABLE 15
Compressive Strength of 1:4:8 Portland Cement Concrete Stored in Sea Water
1 PART TYPICAL PORTLAND CEMENT NO. 47, 4 PARTS JERSEY SAND, 8 PARTS TRAP ROCK

Method of placing concrete in sea water	Age when tested, in weeks	Period of exposure	Test piece number	Weight in pounds per cubic foot	Compressive strength, pounds per square inch			Character of failure	Remarks
					Average	Maximum	Minimum		
Stored in damp room 8 weeks before immersion. Do..... Do.....	13	8/19/09- 9/23/09	71-73	158.3	1756	1905	1623	White deposit found all through the interior of the test pieces. Test piece No. 83 was lost from the storage crate, therefore results contain data on but two test pieces. Only a small amount of white deposit was found in the interior of test pieces. Test piece No. 118, which gave the minimum compression strength value, was imperfectly molded, one end being very porous. White deposit was found to some extent in test pieces Nos. 86 and 88.
	26	8/20/09-12/24/09	77-79	157.9	1916	1966	1827	A, A, A	
	52	8/20/09- 6/25/10	83-85	156.6	1490	1702	1278	A, D	
Stored in damp room 8 weeks before being placed between tides. Do..... Do..... Do..... Do.....	13	9/22/09-10/27/09	118-120	156.5	1256	1590	798	White deposit was found in the interior of test pieces to a depth of about 2 inches from surfaces. Surfaces of test pieces were found to be cracked and swollen in places when removed from the water; a white deposit was in cracks and in interior of concrete. These test pieces were all in bad condition when removed from the water and could not be tested. They were covered with cracks, the cement was soft and "chalky," and concrete could easily be broken apart in hands. In spots cement seemed hard and normal. A white deposit was observed in the interior of all test pieces. These test pieces were all in bad condition when removed from the water, a portion of each being missing, the remainders appearing as described in connection with test pieces Nos. 143-147, above. Water penetrated entirely through test piece No. 127 and to a depth of from 1 inch to 2 inches from cylindrical surfaces and 1/2 inches from end surfaces in test pieces Nos. 128 and 129. Cement of test piece No. 127 seemed soft and "chalky," with large quantities of crystals all through the concrete. While deposit observed in all test pieces.
	13	8/21/09- 9/25/09	86-88	157.0	1159	1338	1056	.....
	13	10/18/09-11/22/09	142-145	157.7	1241	1285	1218	A, A, A	
	26	9/22/09- 1/26/10	121-123	155.7	1447	1627	1239	A, A, D	
	26	10/18/09- 2/21/10	145-147	.....	.....	.....	.....	.....
Do.....	52	9/22/09- 7/28/10	124-126	A, D, A
Do.....	52	9/22/09- 7/28/10	127-129	157.2	1420	1688	983	A, D, A	

TABLE 16
Compressive Strength of 1:4:8 Portland Cement Concrete Stored in Fresh Water
1 PART TYPICAL PORTLAND CEMENT NO. 47, 4 PARTS JERSEY SAND, 8 PARTS TRAP ROCK

Method of placing concrete in fresh water	Age when tested, in weeks	Period of exposure	Test piece number	Weight in pounds per cubic foot	Compressive strength, pounds per square inch			Character of failure	Remarks
					Average	Maxi- mum	Mini- mum		
Stored in damp room 8 weeks before immersion.	13	10/29/09-12/3/09	175-177	156.8	1333	1377	1262	A, A, A	All test pieces completely saturated. No stones sheared.
Do.....	26	10/29/09-3/4/10	178-180	155.4	1574	1591	1554	A, D, D	
Do.....	52	11/3/09-9/8/10	181-183	152.5	1721	1815	1645	A, D, A	
Do.....	104	11/3/09-9/8/11	184-186	155.4	1714	1763	1661	C, A, A	

TABLE 17
Compressive Strength of 1:2:4 Concretes Made with Various Cements and Stored in Sea Water
1 PART TYPICAL PORTLAND CEMENT NO. 47, 2 PARTS JERSEY SAND, 4 PARTS TRAP ROCK

Method of placing concrete in sea water	Age when tested, in weeks	Period of exposure	Test piece number	Weight in pounds per cubic foot	Compressive strength in pounds per square inch	Character of failure	Remarks
Stored in damp room 8 weeks previous to immersion.	13	8/14/09- 9/18/09	34	155.7	3958	No stones were sheared. The concrete appears to be normal.
			35	155.8	3828	.....
			36	157.5	3846	.....
			Av.....	156.3	3877	.....
			37	156.5	3982	A	
Do	26	8/14/09-12/18/09	38	156.7	3978+	No. 37 sheared about 50 per cent of the stones in fracture. Nos. 38 and 39 did not fail under a load of 200 000 pounds, the capacity of the machine. Concrete appears normal.
			39	155.9	3978+	.....
			Av.....	156.4	3979+	.....
			40	156.5	4086	A	
			41	155.9	4054	D	
Do.....	52	8/14/09- 6/19/10	42	157.0	4041	A	Water penetrated to a depth of from 2 to 2½ inches from cylindrical surfaces and from 4 to 5 inches from end surfaces. Surfaces were rough and covered with small "blisters" which shelled off pieces one-eighth to one-eighth inch thick in places. All stones were sheared in fracture.
			Av.....	156.5	4060	.....

TABLE 17—Continued

1 PART GERMAN PORTLAND CEMENT NO. 4, 2 PARTS JERSEY SAND, 4 PARTS TRAP ROCK

Method of placing concrete in sea water	Age when tested, in weeks	Period of exposure	Test piece number	Weight in pounds per cubic foot	Compressive strength in pounds per square inch	Character of failure	Remarks
Stored in damp room 8 weeks previous to immersion.	13	8/1/10- 9/5/10	257	156.5	3743	A	All test pieces saturated to depth of 1 inch in from surfaces. A few stones sheared. No white deposit or crystal were observed.
			258	157.3	3209	D	
			259	155.9	3480	A	
			Av.....	156.5	3477		
			a 260	159.7	4237+		
Do.....	26	8/1/10-12/5/10	a 261	160.8	4237+		None of these test pieces failed under a load of 213 000 pounds, the capacity of the machine. ^a
			a 262	158.6	4237+		
			Av.....	159.7	4237+		
			263	157.8	4237+		
			264	158.0	4237+		
Do.....	52	8/1/10- 6/6/11	265	157.5	4237+		Do.
			Av.....	157.8	4237+		
			266	156.5	6515		
			267	157.2	6167		
			268	151.3	6366		
Do.....	140	8/1/10- 3/-/13	Av.....	155.0	6349		Part of the stones were sheared in each test piece.
						A	
						C	

^a Retested when 1 year old; 261 and 262 did not fail at 213 000 pounds; 260 failed by bulging at 200 000 pounds.

1 PART SLAG CEMENT, 2 PARTS JERSEY SAND, 4 PARTS TRAP ROCK

Stored in damp room 8 weeks previous to immersion.	13	8/24/10- 9/28/10	351 352 353 Av.....	156.5 155.9 156.5 156.3	1753 1772 1692 1739	A A A	All test pieces saturated completely. The outside sections of test pieces were light brown in color, the interior being dark green. No stones sheared.
Do.....	26	8/24/10-12/28/10	354 355 356 Av.....	155.4 156.7 154.6 155.8	1945 2056 1790 1930	A D A	All test pieces were saturated to a depth of 2 inches in from the cylindrical surface and 3 to 4 inches from end surfaces. No stones sheared.
Do.....	52	8/24/10- 6/29/11	357 358 359 Av.....	155.8 154.2 156.3 155.4	1954 1974 1977 1968	A A A	All test pieces completely saturated. A few stones sheared in each test piece.
Do.....	140	8/24/10- 3/-/13	360 361 362 Av.....	153.8 154.2 153.5 153.8	2417 2407 2403 2409	D C B	A few stones were sheared in each test piece.

TABLE 17—Continued

1 PART NATURAL CEMENT NO. 52, 2 PARTS JERSEY SAND, 4 PARTS TRAP ROCK

Method of placing concrete in sea water	Age when tested, in weeks	Period of exposure	Test piece number	Weight in pounds per cubic foot	Compressive strength in pounds per square inch	Character of failure	Remarks
Stored in damp room 8 weeks previous to immersion.	13	4/17/11— 7/17/11	471	153.1	592	C C D	All test pieces saturated throughout.
			472	153.1	630		
			473	152.6	531		
			Av.....	152.9	584		
Do.....	26	4/17/11—10/16/11	474	150.0	1370	A D C	Saturated throughout.
			475	152.0	1192		
			476	149.0	1310		
			Av.....	150.3	1291		
Do.....	52	4/19/11— 6/4/12	483	150.6	1475 C C	Seven weeks overdue when tested.
			484	150.2	1238		
			485	147.0	1058		
			Av.....	149.3	1257		

1 PART SLAG CEMENT NO. 57b, 2 PARTS JERSEY SAND, 4 PARTS TRAP ROCK

Stored in damp room 8 weeks previous to immersion.	13	4/20/12- 7/20/11	495	153.6	1989	All test pieces saturated to depth of 1½ inches.
			496	153.1	1932	
			497	138.5	1931	
			Av.....	155.7	1957	
Do.....	26	4/21/11-10/20/11	498	155.0	2340	Damp throughout; 10 per cent stones sheared.
			499	.....	2541
			500	.....	2525
			Av.....	155.0	2481	
Do.....	52	4/24/11- 6/4/12	507	154.0	3390	About 6 weeks overdue when tested.
			508	133.0	2975	
			509	133.0	2520	
			Av.....	154.7	2962	

TABLE 17—Continued

1 PART SPECIAL NATURAL CEMENT NO. 59, 2 PARTS JERSEY SAND, 4 PARTS TRAP ROCK

Method of placing concrete in fresh water	Age when tested, in weeks	Period of exposure	Test piece number	Weight in pounds per cubic foot	Compressive strength in pounds per square inch	Character of failure	Remarks
Stored in damp room 8 weeks previous to immersion.	13	4/26/11—7/26/11	519	155.8	855	C	All test pieces saturated throughout. No stones sheared.
			520	154.0	857	C	
			521	152.9	811	C	
			Av.....	154.2	841		
Do.....	26	4/27/11—10/26/11	522	1400	C	Damp throughout. No stones sheared.
			523	.....	1410	C
			524	.....	1385	C
			Av.....	.....	1382	
Do.....	52	4/29/11—6/17/11	531	155.0	1625	B	Damp inside. No stones sheared. Seven weeks overdue when tested.
			532	154.0	1565	D	
			533	152.5	1520	A	
			Av.....	155.5	1503		

TABLE 18
Compressive Strength of 1:2:4 Concretes made with Various Cements and Stored in Fresh Water
1 PART TYPICAL PORTLAND CEMENT NO. 47, 2 PARTS JERSEY SAND, 4 PARTS TRAP ROCK

Method of placing concrete in fresh water	Age when tested, in weeks	Period of exposure	Test piece number	Weight in pounds per cubic foot	Compressive strength in pounds per square inch	Character of failure	Remarks
Stored in damp room 8 weeks previous to immersion.	13	9/27/09-11/1/09	130	158.1	3339	A	A few stones sheared.
			131	157.0	3045	A	
			132	158.1	3186	A	
			Av.....	157.7	3190		
Do.....	26	9/27/09-1/31/10	133	157.8	3339	A	Do.
			134	157.5	3367	A	
			135	157.8	3664	A	
			Av.....	157.7	3457		
Do.....	52	10/25/09-8/30/10	157	157.0	3534	A	Water penetrated to a depth of about 3 inches from surfaces. About 50 per cent of stones sheared.
			158	157.0	3572	A	
			159	157.5	3062	D	
			Av.....	157.2	3389		

TABLE 18—Continued

1 PART GERMAN PORTLAND CEMENT NO. 4, 2 PARTS JERSEY SAND, 4 PARTS TRAP ROCK

Method of placing concrete in fresh water	Age when tested, in weeks	Period of exposure	Test piece number	Weight in pounds per cubic foot	Compressive strength in pounds per square inch	Character of failure	Remarks
Stored in damp room 8 weeks previous to immersion.	13	8/4/10-9/8/10	269	157.0	3806	A	All test pieces were completely saturated. A large number of stones sheared. All test pieces appeared normal.
			270	156.7	3665	D	
			271	157.5	3759	A	
			Av.....	157.1	3743		
			272	158.7	4237 +		
Do.....	26	8/4/10-12/8/10	273	158.1	4237 +		Nos. 272 and 273 did not fail under a load of 213 000 pounds. No. 274 was saturated to a depth of 2 inches in from cylindrical surfaces and 3 to 4 inches in from end surfaces. A large number of stones sheared. Concrete appeared normal.
			274	158.6	3987	A	
			Av.....	158.1	4147		
			275	158.0	4237 +		
			276	158.5	4237 +		
Do.....	52	8/4/10-6/9/11	277	158.5	4237 +		All did not fail under a load of 213 000 pounds, the capacity of the machine.
			Av.....	158.7	.....	
			278	158.8	1637	A	
			279	158.8	2045	A	
			280	156.9	2072	A	
1 PART SLAG CEMENT NO. —, 2 PARTS JERSEY SAND, 4 PARTS TRAP ROCK							
Stored in damp room 8 weeks previous to immersion.	13	9/7/10-10/12/10	366	159.7	1803	A	All test pieces were damp entirely through. No. 367 showed 3 or 4 sheared stones.
			367	158.1	1862	C	
			368	159.1	1818	A	
			Av.....	158.9	1828		
			369	154.6	1703	B	
Do.....	26	9/7/10-1/11/11	370	154.8	1790	C	No. 369 was saturated through. No stones sheared. Nos. 370 and 371 seemed perfectly dry, excepting a few places where they were saturated to a depth of 1½ inches in from surface. No. 370, two stones sheared; No. 371, no stones sheared.
			371	155.9	1828	A	
			Av.....	154.8	1774		
			372	150.8	1637	A	
			373	155.8	2045	A	
Do.....	52	9/7/10-7/13/11	374	156.9	2072	A	All test pieces were completely saturated. No stones sheared. No. 372 had several large voids on surface, caused by insufficient tamping.
			Av.....	154.5	1925		

1 PART NATURAL CEMENT NO. 52, 2 PARTS JERSEY SAND, 4 PARTS TRAP ROCK

Stored in damp room 8 weeks previous to immersion.	13	4/17/11-7/17/11	465 466 467 Av.....	150.9 152.6 152.6 152.0	555 532 573 553	C C C	All test pieces saturated throughout.
Do.....	26	4/17/11-10/16/11	468 469 470 Av.....	153.0 149.7 151.8 151.5	1400 1181 1325 1302	C C C	
Do.....	60	4/19/11-6/15/12	477 478 479 Av.....	153.5 151.1 151.5 152.0	1495 1305 1368 1396	C D B	No stones sheared.

1 PART SLAG CEMENT NO. 57b, 2 PARTS JERSEY SAND, 4 PARTS TRAP ROCK

Stored in damp room 8 weeks previous to immersion.	13	4/20/11-7/20/11	489 490 491 Av.....	156.3 155.0 156.1 155.8	1851 1655 1956 1821	C C D	All test pieces saturated to a depth of 1½ inches.
Do.....	26	4/21/11-10/20/11	492 493 494 Av.....	153.2 153.5 152.5 153.1	2623 2722 2400 2582	C A	
Do.....	59	4/24/12-6/15/12	501 502 503 Av.....	155.6 155.7 154.5 155.3	2890 3150 3060 3033	D C A	Damp; stones sheared.

TABLE 18—Continued

1 PART SPECIAL NATURAL CEMENT NO. 59, 2 PARTS JERSEY SAND, 4 PARTS TRAP ROCK

Method of placing concrete in fresh water	Age when tested, in weeks	Period of exposure	Test piece number	Weight in pounds per cubic foot	Com- pressive strength in pounds per square inch	Char- acter of failure	Remarks
Stored in damp room 8 weeks previous to immersion.	13	4/26/12-7/26/11	513	155.8	921	B	
			514	153.0	840	D	
			515	151.5	905	C	
			Av.....	153.4	889		
							Some stones sheared.
Do.....	26	4/27/12-10/26/12	516	152.0	1460	A	
			517	154.0	1471	A	
			518	151.2	1325	A	
			Av.....	152.4	1419		
Do.....	59	4/29/12-6/15/12	525	153.5	1580	A	
			526	149.5	1510	.....
			527	151.5	1492	C	
			Av.....	151.5	1527		

TABLE 19
Compressive Strength of Concrete Stored in Sea Water
1 PART TYPICAL PORTLAND CEMENT NO. 54, 2 PARTS SEASHORE SAND, 4 PARTS TRAP ROCK

Method of placing concrete in sea water	Age when tested, in weeks	Period of exposure	Test piece number	Weight in pounds per cubic foot	Compressive strength in pounds per square inch	Character of failure	Remarks
Stored in damp room 8 weeks before immersion.	13	11/21/10-12/26/10	441 442 443 Av.....	162.9 160.2 161.8 161.6	2698 2675 2527 2633	A A A A	All test pieces were completely saturated. No stones abraded. No white deposit was observed.
Do.....	26	11/21/10- 3/27/11	444 445 446 Av.....	160.6 161.7 161.7 161.0	3141 3159 3308 3203	A A A A	All test pieces saturated to a depth of 1½ inches in front end surfaces and 1 to 1 inch in front cylindrical surfaces. Interiors were damp. A few stones were abraded in test pieces No. 444 and 445.
Do.....	52	11/21/10-10/26/11	447 448 449 Av.....	162.2 160.6 161.2 161.3	3363 3352 3359 3358	A C	All test pieces saturated to a depth of about 2 inches from cylindrical surface and 4 inches from end surfaces. A few stones were abraded.

TABLE 20
Compressive Strength of Concrete Stored in Fresh Water
1 PART TYPICAL PORTLAND CEMENT NO. 54, 2 PARTS SEASHORE SAND, 4 PARTS TRAP ROCK

Method of placing concrete in fresh water	Age when tested, in weeks	Period of exposure	Test piece number	Weight in pounds per cubic foot	Compressive strength in pounds per square inch	Character of failure	Remarks
Stored in damp room 8 weeks before immersion.	4	Not exposed.....	429	157.0	2271	A	These test pieces were taken from damp room when 4 weeks old and tested without immersing in water. All test pieces were damp entirely through. In test piece No. 431 a few stones sheared.
			430	157.0	2313	A	
			431	157.0	2268	A	
			Av.....	157.0	2284		
Do.....	13	11/19/10-12/24/10	432	157.0	2449	A	All test pieces were completely saturated and showed a few sheared stones.
			433	159.1	2539	A	
			434	157.0	2694	D	
			Av.....	157.7	2557		
Do.....	26	11/19/10- 3/25/11	435	158.5	3003	A	All test pieces saturated to a depth of 3 inches except test piece No. 437, which was completely saturated. A few stones sheared in test pieces No. 435 and 436.
			436	159.6	2847	A	
			437	158.4	2219	A	
			Av.....	158.8	2716		
Do.....	52	11/19/10- 9/24/11	438	160.2	2540	A	All test pieces were saturated throughout. Large crystals were observed in test piece No. 438. No stones were sheared.
			439	157.0	3695	C	
			440	159.2	3582	C	
			Av.....	158.8	3339		

TABLE 21

Compressive Strength of Concrete Stored in Sea Water, Fresh Water,
and Damp Atmosphere

1 PART TYPICAL PORTLAND CEMENT TO 6 PARTS PIT RUN "GORGONA"
GRAVEL NO. 55

[Average of 3 test pieces.]

Age in weeks when tested	Method of storing test pieces	Weight in pounds per cubic foot	Ultimate compressive strength in pounds per square inch			Initial modulus of elas- ticity	Yield point, pounds per square inch
			Average	Maxi- mum	Mini- mum		
8	In damp-closet for entire period.....	144.2	1898	1964	1823	2 287 000	533
8	In damp-closet for 4 weeks and fresh water for balance of period.....	148.0	1646	1676	1594	2 575 000	633
8	In damp-closet for 4 weeks and sea water for balance of period.....	147.2	1414	1445	1384	2 457 000	500
13	In damp-closet for entire period.....	144.4	1968	2015	1901	2 457 000	500
13	In damp-closet for 4 weeks and fresh water for balance of period.....	148.1	1825	1890	1786	2 690 000	500
13	In damp-closet for 4 weeks and sea water for balance of period.....	147.7	1655	1684	1598	2 870 000	500
26	In damp-closet for entire period.....	145.6	2172	2241	2083	2 428 000	766
26	In damp-closet for 4 weeks and fresh water for balance of period.....	149.8	2063	2117	1985	2 827 000	866
26	In damp-closet for 4 weeks and sea water for balance of period.....	148.8	2090	2140	1990	3 026 000	800
52	In damp-closet for entire period.....	143.5	2403	2480	2360	2 450 000	733
52	In damp-closet for 4 weeks and fresh water for balance of period.....	148.2	2220	2250	2200	3 710 000	866
52	In damp-closet for 4 weeks and sea water for balance of period.....	148.3	2543	2700	2420	3 567 000	766

TABLE 22

Corrosion Tests of Metal Embedded in Concrete Cylinders Stored in Sea Water

1 PART PORTLAND CEMENT, 1 PART MEREMAC RIVER SAND No. 55, 5 PARTS MEREMAC RIVER GRAVEL No. 54

Number of test piece	Age of test piece, in weeks	Character of metal	Actual position of metal		Depth of penetration of sea water in from surface, in inches	Description of extent of corrosion		Remarks
			Thickness of concrete covering, in inches	Distance of metal from top of cylinder, in inches		Circumferential section	Inferior section	
1	8	Expanded metal, No. 27 gage, $\frac{1}{2}$ -inch mesh.	Expanded metal forming a complete envelope 6 inches wide around outside of cylinder and coiled spirally into the center. (See Fig. 29a.)	$1\frac{1}{2}$	Entirely through.	Heavily corroded; $\frac{1}{4}$ inch rust.	Surface rust, especially near circumferential section.	Concrete hard and sound in appearance.
2	13	do.	do.	$1\frac{1}{2}$	$1\frac{1}{2}$ inches	do.	Light corrosion, especially near circumferential section.	Do.
3	26	do.	do.	$\frac{3}{4}$	2 inches	Very heavily corroded; entirely gone in some places.	Light surface rust, especially near circumferential section.	Do.
4	52	do.	do.	1	$\frac{1}{2}$ -1 $\frac{1}{2}$ inches	Badly rusted and corroded.	Light rust near circumferential section.	Do.
5	8	do.	Expanded metal envelope covered with 1:1 cement mortar plaster for coat $\frac{1}{2}$ inch thick. Same, $1\frac{1}{2}$ inch thick.	$1\frac{1}{2}$ -1 $\frac{1}{2}$	Entirely through.	Slight corrosion near edge.	Slight corrosion in spots.	Do.
6	13	do.	do.	$1\frac{1}{2}$ -1 $\frac{1}{2}$	do.	Medium heavy coating of rust near edges; light rust on entire surface.	Medium heavy rust near edges; rest of section clean.	Concrete appears sound.
7	26	do.	Same, $1\frac{1}{2}$ inch thick.	$1\frac{1}{2}$ -1 $\frac{1}{2}$	do.	Medium heavy coat of rust near edges; entire surface tinged with rust.	Medium heavy rust near edges; rest of section clean.	Concrete appears sound, but there are many rust spots on cylindrical surface.
8	52	do.	Same, $\frac{1}{2}$ inch thick.	$1\frac{1}{2}$	do.	Light coat of rust.	Light coat of rust near the circumferential section.	Concrete very hard, but porous in interior. A few rust spots appear on cylindrical surface.

9	8	Four rods attached to outside of expanded metal. (See Fig. 29b.)	Same, $\frac{1}{2}$ -inch thick, excepting rods exposed.	1-1½	do.	Medium heavy rust, especially near edges; exposed rods heavily corroded.	Lighter coat of rust than on circumferential section near that section; brown tinge on rest of surface.	No rust spots on cylinder surface. Concrete at surface hard and sound.
10	13	do.	Same, $\frac{1}{2}$ -inch thick.	1½-1½	do.	Medium heavy rust, especially near edges; exposed rods heavily corroded.	Light corrosion in spots.	No rust spots on cylindrical surface. Concrete at surface appears hard and sound.
11	26	do.	Same, $\frac{1}{2}$ -inch thick.	1-1½	do.	Medium heavy coat of rust over entire surface; exposed rods heavily corroded.	Corrosion less heavy than on circumferential section.	Small rust spots on cylindrical surface.
12	52	do.	Same, $\frac{1}{2}$ -inch thick.	1½	do.	Medium coat of rust on both sides.	Clean except in few spots, where there was a light rust.	Concrete appears sound, and no rust spots are on cylindrical surface.
13	8	Coil 6 inches diameter and 6 inches long, of ½-inch round iron, 2 turns to inch in height. (See Fig. 29c.)	½-1½ inches thick.	½-1½	do.	Light rust in places.		
14	13	do.	½-1½ inches thick.	½-1½	do.	Heavy surface rust on part of surface.		Large rust spots on surface over place where metal is located.
15	26	do.	1-1½ inches thick.	1½-1½	do.	Corrosion is not uniform, being heavy in places, light in places, and a portion of metal is clean.		
16	52	do.	1½ inches thick.	1-1½	Saturated nearly through.	Coat of medium rust with a few spots where the rust is heavier.		Concrete appears hard and sound.
17	8	Coil 6 inches diameter and 4 inches long, of ½-inch round iron, 2 turns to inch in height. (See Fig. 29d.)	1 inch thick.	1½-2½	Saturated to depth of metal, and a d a m p throughout.	Medium heavy rust in places.		
18	13	do.	½-1½ inches thick.	2½-2½	Entirely through.	Medium light coating of rust.		
19	26	do.	½-1 inches thick.	2½-2½	do.	Corrosion is not uniform, being heavy in spots; brownish tinge over entire surface.		
20	8	Expanded metal.	Expanded metal cone.	1½-1½	Entirely through.	Light corrosion near edges; slight brownish tinge on entire surface.		No rust spots appear on surfaces of cylinder.
21		Same as test piece No. 5.	Expanded metal cone covered with 1:1 cement mortar plaster coat ½-1 inch thick.					

^a The method of placing test pieces 1 to 21, inclusive, in sea water was by storing in crate and immersing in sea; test pieces 21 to 36, inclusive, were placed between tides.

TABLE 22—Continued

Number of test piece	Age of test piece, in weeks	Character of metal	Actual position of metal		Depth of penetration of sea water in from surface, in inches	Description of extent of corrosion		Remarks
			Thickness of concrete covering, in inches	Distance of metal from top of cylinder, in inches		Circumferential section	Interior section	
22	13	Expanded metal. Same as test piece No. 5.	Same, $1\frac{1}{4}$ inch thick.	$1\frac{1}{4}$	4 inches up from bottom; top dry.	Slight brownish tinge.	Clean except in few spots.	No rust spots appear on surfaces of cylinder.
23	26	do.	Same, $1\frac{1}{4}$ inch thick.	$1\frac{1}{4}$	4 inches up from bottom; $\frac{1}{2}$ inch in from other surfaces.	Entire surface covered with light coat of rust; in places rust is medium heavy.	do.	
24	52	do.	Same, $\frac{3}{4}$ inch thick.	$1\frac{1}{4}$	Entirely through.	Metal coated with light rust.	Coated with light rust in places.	Bottom section of cylinder appeared soft and crumbly. A few rust spots appear on surface of cylinder.
25	8	Four rods attached to outside of expanded metal. Same as No. 9.	Same, $1\frac{1}{4}$ inch thick, excepting rods exposed.	$1\frac{1}{4}$	Saturated to depth of 2 inches; damp throughout.	Light corrosion on surface; exposed rods heavily corroded.	Clean except in few spots, where there is light rust.	
26	13	do.	Same, $1\frac{1}{4}$ inch thick.	$1\frac{1}{4}$	do.	Medium heavy coating of rust near edges; rods heavily corroded.	Clean except in 2 spots, where there is a light rust.	Some rust spots appear on surfaces of cylinder.
27	26	do.	do.	$1\frac{1}{4}$	1 inch from top; 2 inches from cylindrical; 3 inches from bottom surface.	Medium heavy coating, except under rods, where metal is heavily corroded; rods badly corroded.	Metal practically clean.	No rust spots appear on surfaces of cylinder.
28	52	do.	Same, $\frac{3}{4}$ inch thick.	$1\frac{1}{4}$	Damp throughout.	Medium coat of rust, particularly near rods; part of metal clean.	do.	Concrete appears hard and sound.
29	8	Cell round iron. Same as No. 12.	$1\frac{1}{4}$ inches thick.	$1\frac{1}{4}$	4 inches from bottom surface; $1\frac{1}{4}$ inches from other surfaces.	Medium heavy coating of rust in places; rest of surface clean.		
20	13	do.	$1\frac{1}{4}$ inches thick.	$1\frac{1}{4}$	Entirely through.	Medium heavy coating of rust; all metal has brownish tinge.		
31	26	do.	1 inch thick.	$1\frac{1}{4}$	3 inches up from bottom; rest of cylinder dry.	Corrosion not uniform, being very heavy in some places; part of metal was clean.		

32	52	do	1-1½ inches thick	1½-2½	Entirely through	Medium heavy rust in places; rest of surface clean.		
33	8	Cell of round iron. Same as No. 17.						
34	13	do	1-1½ inches thick	1½-2½	do	Light coating of rust in places; brownish tinge on all metal.		
35	26	do	1-1½ inches thick	1½-2½	do	Medium coating of rust, heavier in spots; a large portion of metal clean.		
36	52	do	1-1½ inches thick	2-2½	4 inches up from bottom; 1 inch in from other surfaces.	Outside surface slightly heavier rust than inside surface.		Large rust spot on cylindrical surface of cylinder.

TABLE 23
Corrosion Tests of Metal Embedded in Concrete Cylinders Immersed in Sea Water
[Expanded metal to be placed as per Fig. 29c]

Num- ber of test piece	Materials in aggre- gate and prop- ortions. 1 part Portland cement to—	Age of test pieces, in weeks	Actual placing of metal										Description of extent of corrosion of metal		Remarks	
			Thickness of concrete covering, in inches						Distance of metal from top sur- face, in inches				Sheet A	Sheet B		
			Sheet A		Sheet B		Sheet A		Sheet B							
			End I	End II	End I	End III	End I	End II	End I	End III						
37	6 parts pit run gravel No. 55.	8	1	1 $\frac{1}{4}$	1	1 $\frac{1}{2}$	1 $\frac{1}{2}$	1 $\frac{1}{2}$	1	1	1	Very slight corrosion.....	Brownish tinge near top.	Sheet A was entirely covered.		
38		13	1 $\frac{1}{4}$	1	2 $\frac{1}{4}$	1	1	1	1	1	1	Heavy corrosion where ex- posed; light corrosion where covered.	Light corrosion es- pecially at top.	Section 2 inches square of Sheet A near top was exposed.		
39		26	1	1	1	2 $\frac{1}{4}$	1 $\frac{1}{4}$	1 $\frac{1}{4}$	1 $\frac{1}{4}$	1	1	Coating of rust on both sur- faces of metal, being heaviest where exposed.	Lightly rusted along edges.	Section of Sheet A 4 by 1 inches exposed.		
40		52	1	1 $\frac{1}{4}$	1 $\frac{1}{4}$	2 $\frac{1}{4}$	1 $\frac{1}{2}$	1 $\frac{1}{2}$	1 $\frac{1}{2}$	1	1 $\frac{1}{2}$	Slightly rusted in places.....	Light rust near edge at End I.	Sheet A entirely cov- ered; one rust spot on cylinder.		
41	1 part gravel No. 55 below 1-in ch sieve and 5 parts gravel No. 55 above 1-in ch sieve.	78	1 $\frac{1}{4}$ -1	1 $\frac{1}{4}$ -1	1	1 $\frac{1}{2}$	1 $\frac{1}{2}$	1 $\frac{1}{2}$	1 $\frac{1}{4}$	1 $\frac{1}{4}$	1 $\frac{1}{4}$	Badly corroded where ex- posed; heavy rust where covered.	Light rust along edge, especially at End I.	Section 2 by 5 inches of Sheet A was ex- posed by flaking off of concrete.		
42		8	$\frac{1}{4}$	$\frac{1}{4}$	1	2 $\frac{1}{4}$	1 $\frac{1}{2}$	1 $\frac{1}{2}$	1	1	1	Heavily corroded in spots....	Brownish tinge near top.	Sheet A protected only by thin skin of ce- ment.		
43		13	1 $\frac{1}{4}$	1 $\frac{1}{4}$	1	2 $\frac{1}{4}$	1 $\frac{1}{2}$	1 $\frac{1}{2}$	1	1	1 $\frac{1}{4}$	Heavy corrosion where ex- posed.	Very light corro- sion in spots.	Sheet A exposed in spots.		
44		26	1 $\frac{1}{4}$	1 $\frac{1}{4}$	1	2 $\frac{1}{4}$	1	1	1	1 $\frac{1}{4}$	1 $\frac{1}{4}$	Outside surface covered with a medium light coating of rust in places; inside sur- face covered with light coating of rust.	Light surface rust in two places.	Sheet A exposed in places.		
45	Sheet A exposed near top and bottom of cylinder.	52	.....	.....	1	2 $\frac{1}{4}$	1 $\frac{1}{2}$	1 $\frac{1}{2}$	1 $\frac{1}{4}$	1 $\frac{1}{4}$	1 $\frac{1}{4}$	Badly corroded where ex- posed; both surfaces heav- ily rusted.	Metal perfectly clean.	Sheet A exposed near top and bottom of cylinder.
46		78	1 $\frac{1}{4}$	1 $\frac{1}{4}$	1	2 $\frac{1}{4}$	1 $\frac{1}{4}$	1 $\frac{1}{4}$	1 $\frac{1}{4}$	1 $\frac{1}{4}$	1 $\frac{1}{4}$	Badly corroded where ex- posed; both surfaces coated with heavy rust.	Light rust near End I.	Sheet A exposed in one place.		

TABLE 23—Continued

Number of test face	Materials in aggregate and proportion of parts of Portland cement to—	Age of test pieces, in weeks	Actual placing of metal										Description of extent of corrosion of metal		Remarks
			Thickness of concrete covering, in inches		Distance of metal from top surface, in inches										
					Sheet A		Sheet B		Sheet A		Sheet B				
			End I	End II	End I	End II	End I	End II	End I	End II	End I	End II	End I	End II		Sheet A	Sheet B
62	2 parts gravel No. 55 below 1-inch sieve and 4 parts gravel No. 55 above 1-inch sieve.	8	1-1	1-1	1	1	1	1	1	1	1	1	Slight corrosion.....	Extremely slight in spots.	No metal exposed.
63		13	1-1	1-1	1	1	1	1	1	1	1	1	Both surfaces considerably corroded.	Slight corrosion near ends.	Do.
64		26	1-1	1-1	1-1	1-1	1-1	1-1	1-1	1-1	1-1	1-1	Heavily coated with rust.....	Lightly rusted in spots.	No metal exposed. Two rust spots on cylinder surface.
65		52	1	1	1	1	1	1	1	1	1	1	Coated with medium heavy rust.	Lightly rusted near edge.	Sheet A slightly exposed in two places.
66	3 parts gravel No. 55 below 1-inch sieve and 3 parts gravel No. 55 above 1-inch sieve.	78	1	1	1	1	1	1	1	1	1	1	Coated with very heavy coat of rust.	Medium coat of rust near End I.	No metal exposed.
67		8	1-1	1-1	1	1	1	1	1	1	1	1	Slight corrosion in spots; brownish tinge over entire surface.	Slightly corroded in two spots; brownish tinge over surface.	No metal exposed. Rust spots on surface of cylinder.
68		13	1	1	1	1	1	1	1	1	1	1	Both surfaces considerably corroded.	Very slight corrosion near edge.	No metal exposed.
69		26	1	1	1	1	1	1	1	1	1	1	Both surfaces completely covered with rust.	Light rust near edge, especially at End I.	Do.
70		52	1	1	1	1	1	1	1	1	1	1	Both surfaces medium heavy rust.	Light rust near edges.	Do.
71		78	1	1	1	1	1	1	1	1	1	1	Coated with a medium rust.	Light rust near End I.	Do.

TABLE 24
Soundness Test of Pats Made From Various Kinds of Cement

Num- ber of cement	Age when observed	Effect of storing in sea water when 24 hours old			
		Effect of storing in fresh water when 24 hours old	Warping	Cracking	Condition of surface
4	4 weeks	Sound	Slightly warped	Checkering surface	Loose and shelling
	6 months	do	Slightly increased	No change	Cement soft to knife
	12 months	do	No change	do	Cracking off
	22 months	do	do	do	No change
5	4 weeks	do	Slightly warped	Hair and circumferential surface cracks	No change
	6 months	do	do	Cracks deepening	Local swellings
	12 months	do	Badly warped	No change	No change
	22 months	do	1/4-inch convex warp	Checker on under surface; radial cracks	Do
23	4 weeks	do	Considerable	No change	Do
	6 months	do	Very badly warped	Radially	Considerable ^b
	12 months	do	1/4-inch convex warp	No change	No change
	22 months	do	do	do	Do
24	4 weeks	Surface cracking and shelling off	Very slight	No change	Cracking and shelling off
	6 months	No change	No change	do	Cement soft to knife
	12 months	do	do	Radial and circumferential	No change
	22 months	do	1/4-inch convex warp	do	Do
25	4 weeks	Sound	Very slight	Surface hair cracks	Slight ^b
	6 months	do	No change	No change	No change
	12 months	do	do	do	do
	22 months	do	1/4-inch convex warp	do	do
26	4 weeks	do	Slight	Surface hair cracks	Slight ^d
	6 months	do	Badly warped	No change	No change
	12 months	do	No change	do	do
	22 months	do	1/4-inch convex warp	Radial and hair cracks	Cement very soft to knife
27	4 weeks	do	Considerable	No change	No change
	6 months	do	No change	do	do
	12 months	do	1/4-inch convex warp	Radial and hair cracks	Cement soft to knife
	22 months	do	do	do	No change

^a Medium coating of magnesium hydrate; cement hard beneath surface.

^b Medium coating of magnesium hydrate.

^c Very heavy coating of magnesium hydrate.

^d Light coating of magnesium hydrate.

TABLE 24—Continued

Num- ber of cement	Age when observed	Effect of storing in sea water when 24 hours old				Extrusion
		Effect of storing in fresh water when 24 hours old	Warping	Cracking	Condition of surface	
28	4 weeks.....	do.....	Warped.....	Cracked radially and cir- cumferentially hair cracks.	.....	Slight. ^a
	6 months.....	do.....	Considerable.....	No change.....	Cement soft to knife.....	No change.
	12 months.....	do.....	Badly warped.....	do.....	No change.....	Do.
	22 months.....	do.....	1/4-inch convex warp.....	do.....	do.....	Do.
	4 weeks.....	do.....	Considerable.....	Radial and circumferential cracks	.....	Slight. ^b
30	6 months.....	do.....	Very badly warped.....	Increased cracking.....	Starting to burst open.....	No change.
	12 months.....	do.....	Continued increase.....	No change.....	No change.....	Do.
	22 months.....	do.....	1/4-inch convex warp.....	.....	.....	Do.
	4 weeks.....	do.....	Slight.....	Hair cracks.....	Cement medium soft to knife.....	Slight. ^a
	6 months.....	do.....	Badly warped.....	Radial cracks at edge.....	No change.....	No change.
31	12 months.....	do.....	1/4-inch convex warp.....	No change.....	do.....	Considerable.
	20 months.....	do.....	.....	.....	.....	No change.
	4 weeks.....	do.....	Slight.....	.....	Cement soft to knife.....	Slight. ^d
	6 months.....	do.....	No change.....	.....	No change.....	No change.
	12 months.....	do.....	1/4-inch convex warp.....	Circumferentially near edge.....	do.....	Considerable.
32	22 months.....	do.....	Warped.....	Hair cracks.....	Cement soft to knife.....	No change.
	4 weeks.....	do.....	Badly warped.....	No change.....	No change.....	Slight. ^d
	6 months.....	do.....	1/4-inch convex and concave warp.....	do.....	do.....	No change.
	12 months.....	do.....	.....	.....	.....	No change.
	22 months.....	do.....	.....	.....	.....	No change.
33	4 weeks.....	do.....	Slight.....	Slightly hair cracked.....	Cement hard to knife.....	Slight. ^a
	6 months.....	do.....	Considerable.....	No change.....	No change.....	No change.
	12 months.....	do.....	1/4-inch convex warp.....	do.....	do.....	No change.
	20 months.....	do.....	Slight.....	Surface checkered with hair cracks.....	Cement medium soft.....	Slight. ^a
	4 weeks.....	do.....	.....	.....	.....	No change.
34	6 months.....	do.....	Badly warped.....	No change.....	No change.....	Considerable.
	12 months.....	do.....	1/4-inch convex warp.....	.....	do.....	No change.
	20 months.....	do.....	Slight.....	Surface checkered with hair cracks.....	.....	Slight. ^a
	4 weeks.....	do.....	.....	.....	.....	No change.
	6 months.....	do.....	.....	.....	.....	No change.
35	12 months.....	do.....	Badly warped.....	.....	No change.....	Considerable.
	20 months.....	do.....	1/4-inch convex warp.....	.....	do.....	No change.
	4 weeks.....	do.....	Slight.....	Surface checkered with hair cracks.....	Cement medium soft to knife.....	Slight. ^a
	6 months.....	do.....	.....	.....	.....	No change.
	12 months.....	do.....	.....	.....	.....	No change.
36	20 months.....	do.....	Considerable.....	Hair cracks deepening.....	No change.....	Considerable.
	4 weeks.....	do.....	1/4-inch convex warp.....	No change.....	do.....	No change.
	6 months.....	do.....	.....	.....	.....	Slight. ^a
	12 months.....	do.....	.....	.....	.....	No change.
	20 months.....	do.....	.....	.....	.....	No change.
37	4 weeks.....	do.....	Considerable.....	Hair cracks at edges.....	.....	No change.
	6 months.....	do.....	Badly warped.....	Under surface hair cracked.....	.....	Slight. ^a
	12 months.....	do.....	No change.....	No change.....	.....	No change.
	20 months.....	do.....	.....	.....	.....	Do.
	.....	.....	.....	.....	.....	Do.

38	4 weeks.....do	Slight warping increasing	Radial cracks and surface hair cracks.	Slight. ^a No change.
	6 months.....do			
	12 months.....do			
	20 months.....do			
39	4 weeks.....do	Badly warped 1/4-inch convex warp	No change	Considerable. No change.
	6 months.....do			
	12 months.....do			
	20 months.....do			
40	4 weeks.....do	Considerable	Cracked around circumference; checking hair cracks.	Considerable. ^a No change.
	6 months.....do			
	12 months.....do			
	20 months.....do			
41	4 weeks.....do	No change	No change	Do.
	6 months.....do			
	12 months.....do			
	20 months.....do			
42	4 weeks.....do	1/4-inch convex warp	Circumferential hair cracks on surface.	Slight. ^a No change.
	6 months.....do			
	12 months.....do			
	20 months.....do			
43	4 weeks.....do	Considerable	Radial cracks.	Do.
	6 months.....do			
	12 months.....do			
	20 months.....do			
44	4 weeks.....do	No change	Slightly hair cracked	Slight. ^a No change.
	6 months.....do			
	12 months.....do			
	20 months.....do			
45	4 weeks.....do	Considerable	No change	Do.
	6 months.....do			
	12 months.....do			
	20 months.....do			
46	4 weeks.....do	No change	Hair cracks around circumference.	(c)
	6 months.....do			
	12 months.....do			
	20 months.....do			
47	4 weeks.....do	No change	No change	Slight. ^a No change.
	6 months.....do			
	12 months.....do			
	20 months.....do			
48	4 weeks.....do	Very slight	Hair cracks near edge	Do.
	6 months.....do			
	12 months.....do			
	20 months.....do			
49	4 weeks.....do	Considerable	No change	Slight. ^a No change.
	6 months.....do			
	12 months.....do			
	20 months.....do			
50	4 weeks.....do	Increased warping	Cracked radially	Slight. ^a No change.
	6 months.....do			
	12 months.....do			
	20 months.....do			
51	4 weeks.....do	Very slightly	No change	Do.
	6 months.....do			
	12 months.....do			
	20 months.....do			
52	4 weeks.....do	Considerable	Cracked radially	Slight. ^a No change.
	6 months.....do			
	12 months.....do			
	20 months.....do			
53	4 weeks.....do	Increased warping	Hair cracks at edge	Slight. ^a No change.
	6 months.....do			
	12 months.....do			
	20 months.....do			
54	4 weeks.....do	Considerable	Radial cracks	Do.
	6 months.....do			
	12 months.....do			
	20 months.....do			
55	4 weeks.....do	Badly warped	No change	Slight. ^a No change.
	6 months.....do			
	12 months.....do			
	20 months.....do			
56	4 weeks.....do	Warping increasing	Cracked radially, also hair cracks.	No change.
	6 months.....do			
	12 months.....do			
	20 months.....do			
57	4 weeks.....do	No change	No change	Do.
	6 months.....do			
	12 months.....do			
	20 months.....do			
58	4 weeks.....do	1/4-inch convex warp	No change	Do.
	6 months.....do			
	12 months.....do			
	20 months.....do			

^a Medium coating of magnesium hydrate.^b Light coating of magnesium hydrate.^c Fat turned inside out; that is, the top face became flat and bottom curved.^d Very heavy coating of magnesium hydrate.

TABLE 25
Soundness Test of Cement Pats Containing Various Percentages of Plaster of Paris
MIXTURE OF GERMAN PORTLAND CEMENT NO. 4 AND "PLASTER OF PARIS"

Per-centage "Plaster" of Paris added, by weight	Age when observed	Effect of storing in sea water				Condition of surface	Extraneous
		Effect of storing in fresh water	Warping	Cracking	Condition of surface		
0.5	4 weeks.....	Surface cracked, shelling off	Slight		Cracked and shelling off.....	Slight. ^s	
	6 months.....	No change.....	No change.....		Large and small local swell- ings; cement hard.	No change.	
	12 months.....	do.....	do.....		do.....	No change.	
1.0	4 weeks.....	do.....	1/4-inch concave warp		Cracked and shelling off.....	Do.	
	6 months.....	Sound.....	Slight	Some hair cracks	Local swelling.....	Slight. ^s	
	12 months.....	do.....	No change.....	No change	No change.....	No change.	
1.5	4 weeks.....	do.....	do.....	do.....	do.....	Do.	
	6 months.....	Surface cracked, shelling off	1/4-inch concave warp		Cracked and shelling off.....	Considerable. ^s	
	12 months.....	No change.....	Considerable		No change.....	No change.	
2.0	4 weeks.....	Very slightly warped	do.....		do.....	Do.	
	6 months.....	No change.....	1/4-inch convex warp		do.....	Do.	
	12 months.....	Surface cracked and shelling off.....	do.....		Cracked and shelling off.....	Considerable. ^s	
2.5	4 weeks.....	Solvent leaching from under thin edge.....	Considerable		No change.....	No change.	
	6 months.....	Very slightly warped	No change.....		do.....	Do.	
	12 months.....	No change.....	1/4-inch concave warp		do.....	Do.	
3.0	4 weeks.....	Surface cracked, shelling off	Slight		Cracked and shelling off.....	Considerable. ^s	
	6 months.....	Solvent leaching under thin edge.....	No change.....		No change.....	No change.	
	12 months.....	No change.....	do.....		do.....	Do.	
3.0	4 weeks.....	Surface cracked, shelling off	1/4-inch convex warp		Cracked and shelling off.....	Considerable. ^s	
	6 months.....	Solvent leaching under thin edge.....	Considerable		No change.....	No change.	
	12 months.....	Very slightly warped	do.....		do.....	Do.	
	23 months.....	No change.....	1/4-inch concave warp		do.....	Do.	

[illegible]

• Light coating of magnesium hydrate which increases to a medium coating at 7 days.

Medium coating of magnesium hydrate.

TABLE 26
Soundness Tests of Cement Pats Containing Various Percentages of Plaster of Paris
MIXTURE OF PORTLAND CEMENT NO. 5 AND PLASTER OF PARIS

Per centage of plaster of Paris added, by weight	Age when observed	Effect of storing in fresh water	Effect of storing in sea water				Excrecence
			Disintegration	Warping	Cracking	Condition of surface	
0.5	4 weeks	Sound	At thin edge	Very slight	Covered with hair; checking cracks	Slight swellings	Slight. ^(a)
	6 months	do	No change	Increased	Radial cracks	No change	No change.
	12 months	do	do	No change	Radial cracks deepening	do	Do.
	22 months	do	Slight at thin edge	Very slight	Radial cracks deepening	do	Slight.
1.0	4 weeks	do	No change	Increased	Checking hair cracks	Local swellings	Considerable.
	6 months	do	do	Considerable	No change	No change	No change.
	12 months	do	do	1-inch convex warp	Radial cracks	do	Do.
	22 months	do	Slight at thin edge	Slight	Surface hair cracks	Small swelling	Slight.
1.5	4 weeks	do	No change	No change	Badly hair cracked	Local at 2 points	No change.
	6 months	do	Surface bursting	Considerable concave	Checking cracks	do	Local at 2 points.
	12 months	do	No change	1-inch convex warp	No change	Shelling off	No change.
	22 months	do	Slight at thin edge	Slight	Surface hair cracks	Local swelling	Slight.
2.0	4 weeks	do	No change	Increased	Badly hair cracked	Large local swellings	From swellings.
	6 months	do	No change	Considerable concave	Checking	No change	No change.
	12 months	do	do	1-inch concave warp	No change	do	Do.
	22 months	do	At thin edge	Slight	Circumferential hair crack; radial crack	Swelling from cracks	Slight.
2.5	4 weeks	Solvent apparent under thin edge	No change	Increased	Cracks deepening	do	No change.
	6 months	Slightly warped	do	Badly concave	No change	do	Do.
	12 months	No change	do	No change	Hair cracks	do	Slight.
	22 months	Sound	At thin edge	Slight	Hair cracks deepening	Swelling from cracks	No change.
3.0	4 weeks	Solvent apparent under thin edge	No change	Considerable	Deep radial cracks opening up	do	No change.
	6 months	Slightly warped	Surface bursting open	Badly warped concave	Radial crack open $\frac{1}{4}$ inch	do	Do.
	12 months	No change	No change	1-inch concave warp	do	do	Do.
	22 months	No change	No change	do	do	do	Do.

TABLE 26
Soundness Tests of Cement Pats Containing Various Percentages of Plaster of Paris
MIXTURE OF PORTLAND CEMENT NO. 5 AND PLASTER OF PARIS

Per centage of plaster of Paris added, by weight	Age when observed	Effect of storing in sea water					Extraneous
		Effect of storing in fresh water	Disintegration	Warping	Cracking	Condition of surface	
0.5	4 weeks	Sound	At thin edge.	Very slight.	Covered with hair; checker- ing cracks.	Slight swellings.	Slight. (e)
	6 months	do.	No change.	Increased.	Radial cracks.	No change.	No change.
	12 months	do.	do.	No change.	Radial cracks deepening.	do.	Do.
	22 months	do.	Slight at thin edge.	1/4-inch convex warp.	Radial cracks deepening.	do.	Slight. ^a
1.0	4 weeks	do.	No change.	Very slight.	Checkering hair cracks.	Local swellings.	Considerable.
	6 months	do.	No change.	Increased.	No change.	No change.	No change.
	12 months	do.	do.	Considerable.	Checkering hair cracks.	do.	Do.
	22 months	do.	do.	1/4-inch convex warp.	Radial cracks.	do.	Do.
1.5	4 weeks	do.	Slight at thin edge.	Slight.	Surface hair cracks.	Small swelling.	Slight. ^a
	6 months	do.	No change.	No change.	Badly hair cracked.	Local at 2 points.	Local at 2 points.
	12 months	do.	Surface bursting.	Considerable concave.	Checkering cracks.	Large local swellings.	No change.
	22 months	do.	No change.	1/4-inch convex warp.	No change.	Shelling off.	Do.
2.0	4 weeks	do.	Slight at thin edge.	Slight.	Surface hair cracks.	Local swelling.	Slight. ^a
	6 months	do.	No change.	Increased.	Badly hair cracked.	From swellings.	No change.
	12 months	do.	No change.	Considerable concave.	Checkering.	Large local swellings.	Do.
	22 months	do.	do.	1/4-inch concave warp.	No change.	No change.	Slight. ^a
	4 weeks	Solvent apparent under thin edge.	At thin edge.	Slight.	Circumferential hair crack; radial crack.	Issuing from cracks.	Slight. ^a
	6 months	Slightly warped.	No change.	Increased.	Cracks deepening.	No change.	No change.
	12 months	No change.	do.	Badly concave.	Cracks deepening.	do.	Do.
	22 months	Sound.	At thin edge.	No change.	Hair cracks.	Slight. ^b	Slight. ^b
	4 weeks	Solvent apparent under thin edge.	No change.	Considerable.	Hair cracks deepening.	Issuing from cracks.	Issuing from cracks.
	6 months	Slightly warped.	Surface bursting open.	Badly warped concave.	Deep radial cracks opening.	No change.	No change.
	12 months	No change.	No change.	1/4-inch concave warp.	Radial crack open 1/4 inch.	do.	Do.
	22 months	No change.	No change.	do.	do.	do.	do.

Slight. ^b No change.	Deep hair cracks.	Considerably increased.	Slight. Considerably increased.
Do.	Cracked radially.	Badly warped concave.	Badly warped concave.
Do. Slight. ^b No change.	Prominent radial.	1-inch concave warp.	1-inch concave warp.
Do.	Deep hair cracks; deep cracks opening.	Considerably increased.	Considerably increased.
Do. Slight. ^b No change.	Cracked radially.	Badly warped concave.	Badly warped concave.
Do.	No change.	1-inch concave warp.	1-inch concave warp.
Do.	Surface curved with hair cracks.	Considerably increased.	Considerably increased.
Do.	Cracks deep and opening up.	Badly warped concave.	Badly warped concave.
Do. Slight. ^b No change.	Cracked radially.	1-inch concave warp.	1-inch concave warp.
Do.	Cracks continue to open.	Considerably increased.	Considerably increased.
Do.	Deep hair cracks.	Concave warp.	Concave warp.
Do. Slight. ^b No change.	Radial cracks.	1-inch concave warp.	1-inch concave warp.
Do.	No change.	Considerably increased.	Considerably increased.
Do.	Badly swollen.	Very badly concave.	Very badly concave.
Do. Slight. ^b No change.	No change.	Considerable.	Considerable.
Do.	Badly swollen.	Considerably increased.	Considerably increased.
Do.	Badly swollen.	Badly warped concave.	Badly warped concave.
Do.	Badly swollen.	Considerable.	Considerable.
Do.	Badly swollen.	Considerably increased.	Considerably increased.
Do.	Badly swollen.	Very badly concave.	Very badly concave.

^b Light coating of magnesium hydrate which increased to a medium coating at 7 days.



TABLE 26
Soundness Tests of Cement Pats Containing Various Percentages of Plaster of Paris
MIXTURE OF PORTLAND CEMENT NO. 5 AND PLASTER OF PARIS

Per centage of plaster of Paris added, by weight	Age when observed	Effect of storing in sea water				
		Effect of storing in fresh water	Disintegration	Warping	Cracking	Condition of surface
0.5	4 weeks	Sound	At thin edge.	Very slight	Covered with hair; checker-	Slight swellings.
	6 months	do.	No change.	Increased.	ing cracks.	No change.
	12 months	do.	do.	No change.	Radial cracks.	do.
1.0	4 weeks	do.	do.	1/4 inch convex warp.	Radial cracks deepening.	do.
	6 months	do.	Slight at thin edge.	Very slight.	Checkering hair cracks.	Local swellings.
	12 months	do.	No change.	Increased.	No change.	No change.
1.5	4 weeks	do.	do.	Considerable.	Radial cracks.	do.
	6 months	do.	do.	1/4 inch convex warp.	Surface hair cracks.	Slight.
	12 months	do.	Slight at thin edge.	No change.	Badly hair cracked.	Local at 2 points.
2.0	4 weeks	do.	do.	Considerable concave.	Checkering cracks.	No change.
	6 months	do.	Surface bursting.	1/4 inch convex warp.	No change.	Local at 2 points.
	12 months	do.	Slight at thin edge.	Increased.	Surface hair cracked.	Slight.
2.5	4 weeks	do.	No change.	Considerable concave.	Badly hair cracked.	Local swelling.
	6 months	do.	do.	1/4 inch concave warp.	Checkering.	No change.
	12 months	do.	do.	Slight.	No change.	Slight.
3.0	4 weeks	Solvent apparent under thin edge.	At thin edge.	Increased.	Circumferential hair crack; radial crack.	Resulting from cracks.
	6 months	Slightly warped.	do.	Badly concave.	Cracks deepening.	No change.
	12 months	No change.	do.	No change.	No change.	do.
	4 weeks	Sound	At thin edge.	Slight.	Hair cracks.	Slight.
	6 months	Solvent apparent under thin edge.	No change.	Considerable.	Hair cracks deepening.	Resulting from cracks.
	12 months	Slightly warped.	Surface bursting open.	Badly warped concave.	Deep radial cracks opening up.	No change.
	22 months	No change.	No change.	1/4 inch concave warp.	Radial crack open 1/4 inch.	do.

(a)

3.5	4 weeks..... 6 months..... 12 months.....	Slightly warped. Solvent issuing from thin edge. No change.....	At edge. No change..... Bursting open.....	Slight. Considerably increased.....	Deep hair cracks..... Cracked radially..... Prominent radial.....	Badly swollen and shelling off. No change.....	Slight ^b No change..... Do.....
4.0	22 months..... 4 weeks..... 6 months..... 12 months..... 22 months..... 4 weeks..... 6 months.....	do..... Slightly warped. Solvent issuing from thin edge. No change..... do..... do..... do.....	No change..... At thin edge..... No change..... do..... do..... At thin edge..... No change.....	Badly warped concave. 1/4-inch concave warp. Slight. Considerably increased..... Badly warped concave. 1/4-inch concave warp. Slight.	Deep hair cracks; deep cracks opening. Cracked radially..... No change..... Surface covered with hair cracks. Cracks deep and opening up; cracked radially. Cracks continue to open.....	Do..... Slight ^b No change..... Do..... Slight ^b No change..... Do.....	
4.5	12 months..... 22 months..... 4 weeks..... 6 months.....	No change..... do..... Slightly warped. Solvent issuing from thin edge.	Upper and under sur- faces opening. No change..... At thin edge..... No change..... do.....	Badly warped concave. 1/4-inch concave warp. Slight. Considerably increased..... Concave warp.....	Cracks deep and opening up; cracked radially. Cracks continue to open..... Deep hair cracks..... Radial cracks.....	Badly swollen..... No change..... Badly swollen and shelling off both sur- faces. No change.....	Do..... Do..... Slight ^b No change..... Do.....
5.0	12 months..... 22 months..... 4 weeks..... 6 months.....	do..... Slightly warped. Solvent issuing under thin edge; warping in- creased. No change.....	do..... At thin edge..... No change..... Badly disintegrated. Removed from crate. At edge..... No change.....	1/4-inch concave warp. Considerable..... Considerably increased..... Very badly concave..... Considerable..... Considerably increased.....	No change..... Hair cracks..... Deep hair cracks..... Cracked radially.....	No change..... Badly swollen..... Badly swollen.....	Do..... Slight ^b No change..... Do.....
10.0	12 months..... 15 months..... 4 weeks..... 6 months.....	do..... Slightly warped. Solvent issuing under thin edge; warping in- creased. No change.....	do..... At thin edge..... No change..... Badly disintegrated. Removed from crate. At edge..... No change.....	1/4-inch concave warp. Considerable..... Considerably increased..... Very badly concave..... Considerable..... Considerably increased.....	No change..... Hair cracks..... Deep hair cracks..... Cracked radially.....	No change..... Badly swollen..... Badly swollen.....	Do..... Slight ^b No change..... Do.....
15.0	12 months..... 15 months..... 4 weeks..... 6 months.....	Considerably warped; cracked radially. 1/4-inch convex warp.....	do..... Badly disintegrated (re- moved from crate). At thin edge..... No change.....	Badly warped concave..... Considerable..... Considerably increased.....	Cracked radially..... Deep hair cracks.....	Badly swollen.....	Do.....
20.0	12 months..... 15 months.....	Slightly warped. Considerable solvent is- suing under thin edge; warping increased..... Badly warped; radial cracks and surface hair cracks. Missing.....	do..... Badly disintegrated (re- moved from crate). Missing.....	Considerable..... Considerably increased..... Very badly concave.....	Deep hair cracks..... Radial and checkering cracks.....	Badly swollen.....	Slight ^b No change..... Do.....

^b Light coating of magnesium hydrate which increased to a medium coating at 7 days.^a Medium coating of magnesium hydrate.

TABLE 27
Soundness Tests of Cement Pats Containing Various Percentages of Lime
MIXTURE OF PORTLAND CEMENT NO. 5 AND LIME NO. 3

Per cent- age of lime, by weight	Age when observed	Effect of storing in fresh water	Effect of storing in sea water				Efflorescence
			Dismintegration	Warping	Cracking	Condition of surface	
0.5	4 weeks	Sound	At thin edge	Slight, but increasing	Hair cracks	.....	Slight
	6 months	do	No change	Badly warped; convex	Circumferential and radial	.....	No change
	12 months	do	do	1/4-inch convex warp	No change	.....	Do
1.0	4 weeks	do	Thin edge slight	.....	.....	.....	Slight
	6 months	do	No change	Slight	Hair cracks	.....	Do
	12 months	Slightly warped	do	Badly warped	Circumferential and radial	.....	No change
1.5	4 weeks	No change	do	1/4-inch convex warp	No change	.....	At cracks
	6 months	Sound	At thin edge	.....	.....	.....	No change
	12 months	do	No change	Slight, but increasing	Circumferential hair cracks	.....	Slight
2.0	4 weeks	do	do	Badly warped	Circumferential and radial	.....	At cracks
	6 months	do	do	1/4-inch convex warp	No change	.....	No change
	12 months	do	At thin edge	Slight	Hair cracks	.....	Do
2.5	4 weeks	do	No change	Badly warped	Circumferential and radial	.....	Slight
	6 months	Slightly warped	do	No change	Hair cracks	.....	No change
	12 months	do	do	1/4-inch convex warp	Circumferential and radial	.....	At cracks
3.0	4 weeks	Sound	Thin edge	Slight	No change	.....	Slight
	6 months	do	No change	Badly warped	Deep hair cracks	.....	No change
	12 months	Very slightly warped	do	No change	Circumferential and radial	.....	At cracks
3.5	4 weeks	Sound	At thin edge	Considerable	No change	Small local swelling	No change
	6 months	Solvent issuing under thin edge	No change	Badly warped	Circumferential hair cracks	No change	Slight
	12 months	Very slightly warped	do	No change	Circumferential and radial	Small local swelling	No change
4.0	4 weeks	Sound	At thin edge	Slight	No change	No change	At cracks
	6 months	Solvent issuing under thin edge	No change	Badly warped	Hair cracks deepening	.....	Slight
	12 months	Very slightly warped	do	No change	Circumferential and radial	Small local swelling	No change
4.5	4 weeks	Sound	At thin edge	Slight	No change	No change	At cracks
	6 months	Solvent issuing under thin edge	No change	Badly warped	Hair cracks deepening	.....	Slight
	12 months	Very slightly warped	do	No change	Circumferential and radial	Small local swelling	No change
5.0	4 weeks	Sound	At thin edge	Slight	No change	No change	At cracks
	6 months	Solvent issuing under thin edge	No change	Badly warped	Hair cracks deepening	.....	Slight
	12 months	Very slightly warped	do	No change	Circumferential and radial	Small local swelling	No change

4.0	4 weeks. 6 months.	Sound. Solvent issuing under thin edge; slightly warped.	At thin edge. No change.	Slight. Badly warped.	Circumferential hair cracks; deep cracks.	Slight. ^a No change.
4.5	12 months. 4 weeks.	No change. do.	do.	No change.	Circumferential and radial.	At cracks. No change.
	6 months.	Sound. Solvent issuing under edge.	At thin edge. No change.	Slight. Badly warped.	No change.	Slight. ^a No change.
5.0	12 months. 22 months.	No change. do.	do.	No change.	Deep cracks.	No change.
	4 weeks. 6 months.	Sound. Solvent issuing under thin edge.	At thin edge. No change.	Slight. Badly warped.	Circumferential and radial.	At cracks. Slight. ^a Considerable.
10.0	12 months. 22 weeks.	Very slightly warped. No change.	do.	No change.	Circumferential and radial.	At cracks. No change.
	4 weeks. 6 months.	Sound. Solvent issuing under thin edge.	At thin edge. No change.	Slight. Badly warped.	Deep cracks.	Slight. ^a Considerable.
15.0	12 months. 4 weeks.	Very slightly warped. No change.	do.	Very badly warped.	Circumferential and radial.	At cracks. No change.
	6 months. 12 months.	Sound. do.	Thin edge. No change.	Badly warped.	No change.	Slight. ^b Considerable.
20.0	12 months. 4 weeks.	do. do.	Bursting open on under-side.	Very badly warped.	Deep cracks.	No change.
	6 months. 22 months.	do. do.	No change.	Badly warped.	Circumferential cracks burst open; also radial cracks.	Upper surface shelling.
25.0	12 months. 4 weeks.	do. do.	No change.	Very badly warped.	No change.	Continued surface shelling.
	6 months. 12 months.	do. do.	At thin edge. No change.	Badly warped.	Deep circumferential cracks.	Considerable. ^b No change.
50.0	12 months. 4 weeks.	do. do.	do.	Very badly warped.	Radial cracks.	Do. Do.
	6 months. 22 months.	do. do.	At thin edge. Piece broken off.	Slight. Very badly warped.	No change.	Upper surface shelling; continued surface shelling.
50.0	12 months. 4 weeks.	do. do.	Edge breaking off.	Badly warped.	Deep circumferential cracks.	Slight. ^b Considerable.
	6 months. 22 months.	do. do.	Entirely disintegrated (removed from tank).	No change.	Radial cracks.	No change.
50.0	12 months. 4 weeks.	do. do.	Edge breaking off.	Badly warped.	Cracked across center.	Do. Slight. ^c
	6 months. 22 months.	do. do.	Entirely disintegrated (removed from tank).	No change.	Radial cracks before immersion.	No change.

Heavy coating of magnesium hydrate, which fell off in flakes.

TABLE 28

Tensile Strength Results of Two-Year Tests

[Explanation of symbols: M=broken while adjusting in machine. Breaking load probably not over 20 pounds. D=damaged.]

Fig. No.	Dia-gram.	Cement.	Tensile strength in pounds per square inch.											
			Stored in sea water.						Stored in fresh water.					
			1	2	3	4	5	Ave.	1	2	3	4	5	Ave.
37	1	4.....	845	735	840	865	250	707	920	750	770	970	930	868
	2	5.....												
	3	23.....							720	710				715
	4	30b.....	M	87	40			63	706	665	735	660	540	661
	5	30b.....	137	D	D	D	231	194	654	756	869	684		741
38	1	34.....	763	775	877			805	663	811	730			735
	2	35.....	28	86				57	637	670				653
	3	36.....	489	351	85			308	710	728	623			687
	4	37.....	51					51	720	637	670			676
	5	38.....							700	651	771			707
39	1	39.....	62	106	282			151	610	592	618			607
	2	40.....							730	578	708			672
	3	41.....	840	783	756			793	692	670	783			715
	4	42.....							655	610	670			645
	5	43.....	M					M	579	625	525			576
40	1	44.....							704	590	475			590
	2	45.....							670	714				692
	3	47.....							710	678	615	800		701
	4	47.....	142		909	711	238	500	673	565	685	580		626
	5	47.....	647	854	133	674	681	598	705	590	690	570	585	628
41	1	46.....							589	663	654			635
	3	48b.....	297	57	296	180		207	744	751	661	665	756	715
	4	48b.....	96	566	681	52	775	434	630	695	715	655	795	698
	5	53.....	860	835	910	730	835	834	775	660	745	850	650	736
	1	60.....	560	640	510	540	650	580	790	755	880	680	985	818
42	2	55.....	20	28	262	D	120	107	713	590	662	692	705	672
	4	24b.....	51	89	96	160	71	93	735	670	572	830	730	707
	2	26b.....	35	50	58	D	D	48	303	337	262	300	293	299
	3	26b.....	104	55	223	65	91	108	340	365	330	335	308	336
	4	27.....	57	M				57	484	466	375			442
43	5	28.....	197	116	54			122	363	345	340			349
	1	32.....	281	162	426			290	465	434				450
	2	33.....	165	90	47			101	332	308				320
	3	52.....	260	130	80	275		186	340	325	375	300	320	333
	4	57.....	88	98	113	70		92	780	720	645	755	705	721
44	5	57b.....	610	765	570	480	680	621	425	510	440	610	535	504
	1	48d.....							361	358	321	405		361
	2	23ed.....	153	104	141	125		131	250	205	243	260	198	231
	3	23ed.....	137	203	275			205	180	230	220	278		227
	4	24b ed.....	195	270	210	290		241	330	350	355	370		351
45	5	30b ed.....	164	165	177	140		161	286	262	320	312	334	303
	1	47ed.....	367	309	275	121	258	266	236	260	304	245	266	262
	2	52ed.....	104	134	113			117	392	321	290	303	365	337
	3	55ed.....	176	240	243	241	138	208	315	490	400	415	380	400
	4	57b ed.....	310	300	330	330	315	317	405	350	405	325	405	378
46	5	60ed.....	335	330	275	380	305	325	395	400	385	405	395	396
	1	4.....	845	735	840	865	250	707						
	2		737	763	732	673	692	719	875	880	750	860	935	860
	3		615	537	588	690	600	606	592	880	800	785	700	751
	4		518	553	419	578	302	474	820	640	665	865		747
47	5		503	43	393	372	538	370	700	690	830	675		724
	1		632	657	625			638	760	715	895	820	760	790
	2	4 with plaster of Paris added.....	390	306	374	557	481	422	705	715	750	678	790	728
	3		396	351	305	246	525	365	738	775	612	620		686
	4		285	336				310	685					685
48	5		434	400	419	465	453	437	775	685	630	708	625	685
	1		525	626	115	345	414	405	740	683	708	645	750	705
	2		383	476	449	526		458	644	665	690	725	640	673
	3		386	494	449			443	743	640	700	725	620	686
	4	24b.....	51	89	96	160	71	93	735	670	572	830	730	707
49	5		15	83	76			58	738	690	600	620		662
	1	24b with plaster of Paris added.....	86	172	105	68		108	558	595	585	690	750	636
	2								460	570	620			550
	3		280	364	252	304		300	525	540	600	660	665	598
	4		120	40				80	490	312	535	225	320	376

TABLE 28—Continued

Fig. No.	Dia-gram.	Cement.	Tensile strength in pounds per square inch.											
			Stored in sea water.						Stored in fresh water.					
			1	2	3	4	5	Ave.	1	2	3	4	5	Ave.
51	3	47.....							710	678	615	800	.....	701
	4		M	30	.....	.....	.....	30	645	665	735	790	695	706
	5								815	820	780	705	790	782
	1		M	130	M	.....	.....	130	715	740	720	695	680	710
	2		100	365	215	75	M	189	670	855	690	810	685	742
52	3	47 with plaster of Paris added.....	430	415	450	455	.....	437	780	680	855	655	970	788
	4		400	415	270	400	340	365	895	785	820	1025	830	871
	5		395	430	550	.....	.....	458	870	680	795	875	690	782
	1		220	395	385	355	350	341	800	630	740	760	865	759
	2		520	480	400	570	450	484	660	580	745	685	770	688
53	3		460	480	570	.....	.....	503	845	720	600	.....	.....	722
	a 4													
	a 5													
	1	52.....	260	130	80	275	.....	186	340	325	375	300	320	333
	2	52 with plaster of Paris added.....							345	340	400	.....	.....	362
54	3								325	272	.....	.....	.....	298
	4	24b.....	51	89	96	160	71	93	735	670	572	830	730	707
	5		30	40	70	D	.....	47	355	560	640	.....	.....	518
	1	24b with ammonium carbonate.....	70	90	80	M	.....	80	660	400	475	655	480	534
	2		M	M	M	D	D	.....	530	450	510	380	520	478
55	3	24b sd.....	195	270	210	290	.....	241	330	350	355	370	.....	351
	4		222	203	292	260	.....	244	495	442	458	407	.....	450
	5	24b sd with ammonium carbonate.....	192	232	140	265	.....	207	397	420	387	429	300	387
	1		225	227	183	300	149	217	375	351	344	362	287	344
	2		227	136	214	251	221	210	440	450	455	425	435	441
56	3	47.....							710	678	615	800	.....	701
	4	47 with ammonium carbonate.....	D	M	20	M	.....	20	790	685	760	765	880	776
	5		M	20	.....	.....	.....	20	670	560	480	610	650	594
	1	47 sd.....	367	309	275	121	258	266	236	260	304	245	266	262
	2		150	180	200	210	180	219	280	280	260	300	270	278
57	3	47 sd with ammonium bonate.....	180	180	160	190	170	170	320	280	300	280	.....	276
	4		161	211	213	131	.....	179	355	350	340	368	405	364
	5		M	35	.....	.....	.....	35	660	590	680	770	660	672
	1	52.....	260	130	80	275	.....	186	340	325	375	300	320	332
	2	52 with ammonium carbonate.....	100	420	30	340	.....	222	345	350	380	310	390	355
58	3		M	320	D	300	330	317	355	365	280	325	340	333
	4		145	85	125	M	100	114	325	355	300	310	335	325
	5	52 sd.....	104	134	113	.....	.....	117	392	321	290	303	365	334
	1		M	108	105	167	92	118	245	295	303	.....	.....	281
	2	52 sd with ammonium carbonate.....	130	220	152	255	158	183	295	265	230	268	308	273
59	3		140	126	136	140	179	144	270	303	237	294	288	278
	4								230	320	335	363	345	319
	5													

* Badly swollen, so could not be tested.



(Continued from page 6 of cover.)

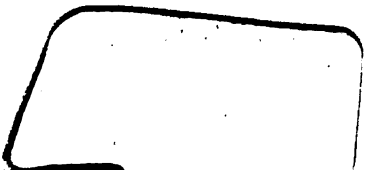
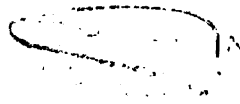
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